

Assessing the effects of prescribed fire on foraging bats at Mammoth Cave National Park
after the arrival of White-nose Syndrome

By

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By

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DEDICATION

This thesis is dedicated to my parents, Guy and Cynthia Griffiths, who provided steadfast support through all my academic career, helped me achieve my dream of a higher education, and taught me to always do my best.

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Abstract

Habitat use of bats may shift following population level impacts of White-nose Syndrome (WNS). Multiple bat species have experienced unprecedented population declines due to WNS, including federally listed *Myotis sodalis* (Indiana bat) and *Myotis septentrionalis* (northern long-eared bat). Specifically, the effect of WNS across forest landscapes is unclear in relation to prescribed fire. Mammoth Cave National Park (MACA) has employed a prescribed fire regime since 2002 and WNS was detected on MACA in 2013. Bat activity was monitored across burned and unburned sites at MACA before (2010-2012) and after the detection of WNS (2013-2016) using transects of acoustic detectors (Anabat II and Songmeter SM3). Recordings were classified to phonic groups (low, mid, *Myotis*) and species using automated classifiers (Bat Call Id v.2.7c and Kaleidoscope Pro v.3.1.4B). Subsequent analyses were conducted using bat passes with $5 \leq$ pulses, with a 95% or 70% confidence interval for species and phonic group classification, respectively. Insect traps (blacklight and malaise) were deployed concurrent with acoustic transects and insects were identified to order. There was a significant interaction between WNS and prescribed fire for the *Myotis* phonic group ($P < 0.01$), with the greatest activity shifting from unburned areas before WNS to burned areas after WNS. Total insect abundance was greater after WNS ($P < 0.01$). Abundance was greater after WNS and in unburned areas for Lepidoptera ($P < 0.01$) and burned areas Coleoptera ($P < 0.05$). Diptera abundance did not change over the course of the study ($P \geq 0.05$). These data indicate substantial changes in both predator and prey community composition at MACA. I used multiple linear regression in conjunction with Akaike's Information Criterion to determine the most the most parsimonious model for predicting

M. sodalis and *M. septentrionalis* activity in a post-WNS landscape. The only significant model developed considered landscape attributes ($P < 0.05$); this model provided the best fit for both *M. sodalis* and *M. septentrionalis* response variables. Parameter estimates were significant for aspect in the landscape model for *M. sodalis* ($P < 0.05$), suggesting a negative relationship with this physiographic variable. However, these data were exploratory and demonstrate a need to further investigate the habitat use of these two imperiled species. In summary, bat activity across MACA has been altered as a result of WNS and prescribed fire. Species impacted by WNS have declined across the landscape, with activity increasing for species not susceptible to WNS. Burned areas across MACA experienced greater levels of bat activity after WNS. Thus, forest managers should take prescribed fire and landscape features into consideration when managing for bat population impacted by WNS.

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Chapter 1

Change in activity of *Myotis sodalis* and *Myotis septentrionalis* on the landscape of Mammoth Cave National Park following the arrival of White-nose Syndrome

Introduction

White-nose Syndrome (WNS) is a disease associated with the psychrophilic fungus, *Pseudogymnoascus destructans*, and has resulted in the death of more than six million bats (Gargas et al. 2009; Frick et al. 2010; Coleman and Reichard 2014). WNS was discovered during the winter of 2006 – 2007 in the state of New York and has currently spread to 30 states and 5 Canadian provinces (USFWS 2011; Alves et al. 2014). To-date, seven cave hibernating bat species have been confirmed to be affected by WNS (USFWS 2015a). Several *Myotis* species are affected by WNS, including the federally listed *Myotis sodalis* (Indiana bat) and *Myotis septentrionalis* (northern long-eared bat).

Myotis sodalis was listed as an endangered species in 1967 (USFWS 2006) and is currently protected under the Endangered Species Act of 1973. Factors contributing to population declines of this species include: habitat destruction, disturbance during hibernation, disease, and predation (USFWS 2006). *Myotis sodalis* is an insectivore that roosts singly or in maternity colonies during the summer, and hibernates in caves or mines during the winter (Davis 1974; Thomson 1982). Since *M. sodalis* has been listed as an endangered species for many years, a prodigious amount of research has been focused on its recovery and monitoring. Past recovery efforts for *M. sodalis* have largely concentrated on preventing habitat destruction and human disturbance during hibernation

(USFWS 2006). WNS poses a different threat to the survival of this species due to biologists' limited knowledge of the causal effects of the fungus, and the difficulty of preventing the spread of the disease. The effect of WNS on populations of *M. sodalis* has been well documented through hibernaculum counts and summer surveys. Population estimates for *M. sodalis* fell from 635,349 individuals in 2007 to 523,636 individuals in 2015 (USFWS 2015b). While the decline of *M. sodalis* has been well-documented, less sound estimates exist for some species, including *M. septentrionalis*.

Myotis septentrionalis was listed as a federally threatened species in April 2015 (USFWS 2015c). WNS has spread across 60% of the distribution of *M. septentrionalis*, and has resulted in unprecedented declines for this once common species (USFWS 2015c). *Myotis septentrionalis* is an insectivore that roosts in live or dead trees during the summer, either singly or in maternity colonies (Caceres and Barclay 2000; Reid 2006). *Myotis septentrionalis* is not a colonial hibernator; instead it hibernates singly in crevices or cracks of cave walls and are often overlooked during hibernaculum counts, rendering accurate population estimates difficult to achieve (Davis 1974; Steve Thomas, NPS, pers. comm.). Populations of this species were thought to be stable until the arrival of WNS; now this disease poses a serious threat to the persistence of *M. septentrionalis* (Coleman and Reichard 2014; USFWS 2015c).

WNS has continued to spread across North America, and threatens *M. sodalis* and *M. septentrionalis* across the majority of their distributions. Hibernaculum counts have confirmed over-winter population declines of both species (Coleman and Reichard 2014), but the decline of these populations have largely been undocumented across Kentucky's

landscape during summer months. My objective was to determine the effect of WNS on the activity of these *Myotis* species across the landscape at Mammoth Cave National Park (MACA). I hypothesized that following the detection of WNS activity of *M. septentrionalis* and *M. sodalis* across the landscape at MACA would decrease.

Study Area

Mammoth Cave National Park is a 23,000-ha parcel of land located in portions of Barren, Edmonson, and Hart counties on the edge of the Crawford-Mammoth Cave Uplands of the Interior Plateau of Kentucky (Woods et al. 2002). MACA has extensive limestone cave systems, in which *M. sodalis* and *M. septentrionalis* are known to hibernate (NPS 2012; Lacki et al. 2015). The National Park Service implemented a WNS management plan (NPS 2012); WNS was detected in the Park in January 2013 (NPS 2013). The vegetation on MACA is primarily composed of deciduous, oak-hickory forests with white oak (*Quercus alba*), black oak (*Q. velutina*), southern red oak (*Q. falcata*), pignut hickory (*Carya glabra*), and post oak (*Q. stellata*) (NPS 2011). Maple (*Acer spp.*), white ash (*Fraxinus americana*), and yellow poplar (*Liriodendron tulipifer*) are found in mesic areas; riparian areas have sweet gum (*Liquidambar styraciflua*), red maple (*Acer rubrum*), sycamore (*Platanus occidentalis*), birch (*Betula spp.*), and hackberry (*Celtis spp.*) (Woods et al. 2002).

Methods

Bat activity was monitored across MACA prior to detection of WNS (2010 – 2012) and after detection of WNS (2013 – 2015). Bat activity was assessed from April-September each year using Anabat II acoustic detectors (Titley Electronics, Colombia, MO). Detectors were housed in plastic protective cases and powered with external batteries; microphones were deployed 1.5-m above the ground (Dodd et al. 2013; Appendix 4). Acoustic surveys spanned multiple consecutive nights to account for nightly variation of bat activity throughout the growing season. Detectors were deployed at randomly established transect sites across a variety of habitats (n = 74 detector locations, Figure 1.1, Figure 1.2) and regularly calibrated (Dodd et al. 2013). I used Kaleidoscope v.1.2 (Wildlife Acoustics, Maynard, MA) to download acoustic data (zero-crossing format) collected from sunset to sunrise. I used an automated program (Bat Call ID v.2.7c) to classify recorded bat passes according to phonic group and species. Bat passes containing ≥ 5 pulses were assigned classifications. Classification of the *Myotis* phonic group and species were conducted at $\geq 70\%$ and $\geq 95\%$ confidence levels, respectively. My response variables for bat activity were the number of passes per detector / night for the *Myotis* phonic group, *M. septentrionalis*, and *M. sodalis*; these variables were considered in relation to WNS arrival to MACA (pre-detection vs. post-detection). We did so using the program 'R' v.3.1.2 (R Development Core Team 2012) and performed Student's t-tests.

Results

I recorded a total of 7,379 bat passes (consisting of 89,250 echolocation pulses) over 1,390 detector / nights across all years. For *M. septentrionalis*, 677 passes (consisting of 5,406 pulses) were recorded before the detection of WNS and no passes were recorded after the detection of WNS. For *M. sodalis*, 60 passes (consisting of 416 pulses) were recorded before the detection of WNS and only a single pass (consisting of 5 pulses) was recorded after the detection of WNS. The number of passes classified as the *Myotis* phonic group decreased from 3,867 passes (consisting of 44,604 pulses) before the detection of WNS to 70 passes (consisting of 755 pulses) after the detection of WNS. The number of bat passes per detector / night classified as the *Myotis* phonic group, *M. septentrionalis*, and *M. sodalis*, all decreased significantly following arrival of WNS ($P < 0.01$, Table 1.1, Figure 1.3).

Discussion

WNS produces mortality in affected bat species by increasing arousal times from torpor, leading to dehydration and depletion of fat reserves, resulting in death of infected bats (Willis et al. 2011; Reeder et al. 2012). WNS has increased the levels of overwinter mortality of *M. sodalis* and *M. septentrionalis* in MACA, resulting in declines in winter populations (Thomas 2016). These species are primary predators of nocturnal insects (Davis 1974), and their recent declines could lead to adverse effects throughout the entire MACA ecosystem (Boyles et al. 2011).

My findings at MACA are consistent with acoustic surveys conducted before and after the detection of WNS in other localities (Dzal et al. 2011; Coleman et al. 2014).

WNS can have an indirect impact on bat species which are not susceptible to WNS infection. The decline of *Myotis* species can potentially alter niche partitioning of bat species within a forest community (Jachowski et al. 2014), with bat species not affected by WNS, e.g. *Lasiurus borealis* (eastern red bat) and *Nycticeius humeralis* (evening bat), expanding their use of habitats previously occupied by WNS impacted species.

Decreasing populations of *Myotis* species could potentially increase the amount of resources available to other bat species through reduced levels of competition.

Chapter 2

Effects of prescribed fire and white-nose syndrome on bat activity across the landscape of Mammoth Cave National Park, Kentucky

Introduction

All bats in eastern North America use echolocation for orientation during flight and for locating prey (Barbour and Davis 1969; Holderied and von Helversen 2003). While individual species have unique call structures, phonic qualities can be generalized across taxa (Aldridge and Rautenbach 1988). These generalizations are based on the frequencies used in echolocation (kHz), and broad distinctions can be made across low-, mid-, and high-frequency phonic groups (Lacki et al. 2007). Notable for management of forested habitats in North America, species within the high-frequency phonic group belong to the genus *Myotis*. Species within a given phonic group share a suite of similar morphological features related to wing aspect ratio (length of the wing divided by its surface area; AR) and wing loading (mass of the bat divided by its total wing area; WL) (Cox et al. 2016). These morphological characteristics are hypothesized to broadly determine habitat suitability across phonic groups (Lacki et al. 2007).

Bat phonic groups tend to select varied forest canopy conditions when foraging. High-frequency species (i.e., *Myotis*) broadly possess low to moderate AR, low WL, and echolocate at higher frequencies. Thus, *Myotis* species tend to select cluttered forest canopies [closed-space foragers, *sensu* Law et al. (2016)] due to their wing shape, which allows these bats to fly slower with a higher degree of maneuverability; and their high-

frequency echolocation calls, which travel shorter distances, are emitted at a faster rate (Harvey et al. 1999; Jantzen and Fenton 2013). Low-frequency species such as *Lasiurus cinereus* (hoary bat), *Lasionycteris noctivagans* (silver-haired bat), and *Eptesicus fuscus* (big brown bat) tend to have high AR, moderate to high WL, and echolocate at lower frequencies. Thus, low-frequency bats tend to select uncluttered spaces or open forest canopies [open-space foragers *sensu* Law et al. (2016)], due to wing characteristics allowing for faster flight speeds; and low-frequency echolocation which travels greater distances, are emitted at a slower rate (Schnitzler and Kalko 2001; Lacki et al. 2007; Altringham 2011). Mid-frequency species such as *Nycticeius humeralis* (evening bat), *Lasiurus borealis* (eastern red bat), and *Perimyotis subflavus* (tricolored bat) can forage effectively in both open and closed canopies due to moderate AR (but varied WL). Such a characteristic allows these bats faster flight than high-frequency bats and more maneuverability than low-frequency bats (Altringham 2011; Jantzen and Fenton 2013).

While morphological characteristics may better suit a given bat species to forage in a particular habitat, it does not restrict them to a single habitat structural configuration. Despite the aforementioned generalizations, patterns of habitat use do vary within a bat phonic group. Variation in selection of foraging areas among habitat types exists across *Myotis* species. For example, *Myotis lucifugus* (little brown bat) and *Myotis grisescens* (gray bat) often forage in forested riparian areas; while *Myotis sodalis* (Indiana bat), *Myotis septentrionalis* (northern long-eared bat) and *Myotis leibii* (small-footed bat) are known to forage in upland habitats with cluttered canopies (Harvey et al. 1999; Reid 2006; Lacki et al. 2007). While these congeners have characteristics defining them as closed-space foragers, individual species select foraging sites of varying size, location,

and topography (Brack 2006; Lacki et al. 2007; Silvis et al. 2016). Clearly, more than one habitat characteristic needs to be considered when managing forested habitats for the *Myotis* genus.

The structure of a forest canopy is important to consider when managing habitats for bat species, as altering the canopy can lead to a shift in community composition of bats (Aldridge and Rautenbach 1988; Adams and Thibault 2006). Silvicultural practices in eastern North America alter the composition and structure of deciduous forests with goals of maintaining historical plant composition, reducing stem density, and mimicking historical disturbance events (Brose et al. 2001; Arthur et al. 2012). Prescribed fire is employed as a forest management tool to promote oak regeneration, reduce fuel accumulation, and increase the growth of herbaceous plants in the understory (Shumway et al. 2001; Burton 2013). Prescribed fire alters vegetative composition by removing fire intolerant species, decreasing canopy clutter, and potentially increasing the number of snags (Perry 2012). The response of bats to fire varies across phonic groups. Buchalski et al. (2013) found that open space foragers had no response to prescribed fire; while *Myotis* species had a positive response to prescribed fire. This is counter to expectation, because *Myotis* species forage in cluttered canopies. Buchalski et al. (2013) study was conducted in western North America; which has a different forest structure and species composition compared to the deciduous forests of eastern North America. Cox et al. (2016) conducted a study in Tennessee examining the effects of prescribed fire and timber harvesting on bat activity. They found that open-space foragers exhibited a greater increase in activity relative to closed-space foragers and overall bat activity increased with fire and increased timber harvest intensity. Given the inconsistency of results from field studies (Silvis et al.

2016), our understanding of the effects of prescribed fire on bat activity remains limited and in need of further research.

Historically, the effects of silviculture and human disturbance have been focal concerns for research and management of forest bats in eastern North America; but the effects of an emerging disease now need to also be considered. White-nose syndrome (WNS) has resulted in unprecedented declines of many bat populations and threatens their persistence across North America (Alves et al. 2014; USFWS 2015a). WNS is a disease associated with the psychrophilic fungus, *Pseudogymnoascus destructans*, and has resulted in the death of millions of bats (Gargas et al. 2009; Frick et al. 2010; Jachowski et al. 2014). The *Myotis* phonic group has been severely impacted by WNS, with *M. lucifugus*, *M. sodalis*, and *M. septentrionalis* experiencing $\geq 90\%$ mortality rates in affected hibernacula (Fenton 2012; Coleman and Reichard 2014; USFWS 2015a). Bat species in other phonic groups have been less-severely impacted. While *P. subflavus* (mid-frequency) and *E. fuscus* (low frequency) also contract WNS (USFWS 2015a); only *P. subflavus* is experiencing significant declines whereas *E. fuscus* has not shown any deleterious WNS related population-level effects from the fungus (Coleman and Reichard 2014; Frank et al. 2014).

Declines of cave hibernating bat species can lead to altered niche partitioning across the landscape. Jachowski et al. (2014) used acoustic monitoring to determine the impacts of WNS on niche partitioning of individual bat species within an eastern deciduous forest. They found that after the decline of *M. lucifugus*, other bat species shifted their spatiotemporal use of habitats to areas that were formerly frequented by *M.*

lucifugus. Comparing data from before and after the arrival of WNS in an ecosystem can provide information on how this disease may impact bat communities, but few studies have had this opportunity. The objectives of this study were to: 1) determine the impacts of prescribed fire on the activity of bats across the landscape of MACA, 2) document changes in habitat use by foraging bats following arrival of WNS to the Park, and 3) assess the relative availability of insect populations concurrent with surveys of bat activity. I predicted that: 1) activity levels of low and mid phonic groups of bats would be greater in burned habitats due to reduced canopy clutter, 2) there would be a decline in activity of the *Myotis* phonic group in both burned and unburned habitats across MACA due to WNS, 3) the observed activity of low- and mid- frequency bats, which are less affected by WNS, would increase because of less competition with declining *Myotis* species, and 4) the abundance of insect prey would increase due to decreased predation pressure from reduced populations of foraging bats.

Study Area

Mammoth Cave National Park consists of 23,000-ha on the edge of the Crawford-Mammoth Cave Uplands of the Interior Plateau of Kentucky, which encompasses the longest cave system in the world and is bisected by the Green River (NPS 2001; Woods et al. 2002). MACA is a karst landscape, with a mean annual precipitation of 107-130 cm, a mean low temperature of -6°C in January, and a mean high temperature of 33°C in July (Woods et al. 2002). Deciduous, oak-hickory forests located on upland ridges are composed of white oak (*Quercus alba*), black oak (*Q. velutina*), southern red oak (*Q.*

falcata), pignut hickory (*Carya glabra*), and post oak (*Q. stellata*) (NPS 2011). Mesic areas are composed of maple (*Acer spp.*), white ash (*Fraxinus americana*), and yellow popular (*Liriodendron tulipifer*); riparian areas have sweet gum (*Liquidambar styraciflua*), red maple (*Acer rubrum*), sycamore (*Platanus occidentalis*), birch (*Betula spp.*), and hackberry (*Celtis spp.*) (Woods et al. 2002). A fire management plan was implemented at MACA with the goal to “...maintain and restore ecological processes that existed before settlement within the park lands...” (NPS 2001, p. 19). To-date, the National Park Service (NPS) has established seven burn units across a variety of habitats in MACA; with burns taking place since 2002 (Figure 2.1). All burn units have been burned at least once; with four units or portions of units being burned more than once (Figure 2.2). The first detection of WNS in Kentucky was in Trigg County during the winter of 2011 - 2012 (Hines and Armstrong 2014). In response to this, the NPS implemented a WNS management plan (NPS 2012), with WNS first detected in the Park in January 2013 (NPS 2013).

Methods

Bat Activity

Bat activity on MACA was monitored prior to detection of WNS (2010 – 2012) and after detection of WNS (2013 – 2016). Bat activity was assessed from April-September each year using zero-crossing acoustic detectors (Anabat II system, Titley Electronics, Colombia, MO). Detectors were housed in plastic protective cases and powered with external batteries, with microphones deployed 1.5-m above ground (Dodd

et al. 2012; Appendix 4.). Detectors were deployed in randomly generated transects within each burn unit and a corresponding control unit with no history of prescribed fire (Figure 2.3) (Dodd et al. 2013). Transects composed of four detectors were deployed 100 m apart starting from the edge of a burn unit and moving towards the interior (i.e., resulting transects were 0.5 km in length). Acoustic surveys spanned multiple consecutive nights to account for nightly variation of bat activity throughout the growing season. Detectors were operated in at least one or more burn sites and one or more unburned sites simultaneously during a monitoring session to account for temporal and spatial variation (Dodd et al. 2012).

Insect Communities

Blacklight traps were used to sample the nocturnal phototactic insect community and malaise traps were used to sample the non-phototactic insect community (Southwood 1987) on MACA. Deployment of insect traps followed Dodd et al. (2012). A blacklight trap and malaise trap were operated for a single night concurrent with each acoustic detector during each sampling interval (Figure 2.3). Traps were operated from sunset to sunrise on clear nights with temperatures $\geq 16^{\circ}\text{C}$ (Yela and Holyoak 1997). Reference keys were used to identify insects to order (Borror and White 1970; Triplehorn and Johnson 2005).

Analysis

Multiple automated identification procedures were used to ensure the accuracy of species-level identifications from acoustic surveys conducted on MACA (Britzke et al.

2011). Kaleidoscope v.1.2 (Wildlife Acoustics, Maynard, MA) was used to download acoustic data (zero-crossing format). Echolocation sequences containing ≥ 5 pulses were quantified as “passes” (i.e., a sequence of continuous pulses) and identified to species using the reference libraries and automated classifiers of Kaleidoscope Pro v.3.1.4B and Bat Call ID v. 2.7c (BCID; Kansas City, MO). When possible, the reference library specific to Kentucky was used for species identification. Additionally, echolocation calls were identified to low, mid, or *Myotis* (high) frequencies using BCID. Echolocation calls < 30 kHz were classified as low phonic group, calls between 30 – 60 kHz as mid phonic group, and all higher-frequency calls by *Myotis* species were classified to that nominal grouping. Only passes assigned a 70% confidence interval or greater for phonic group identification were used for analysis (Fulton et al. 2014). Subsequent response variables were the number of passes per detector / night for the low, mid, and *Myotis* phonic groups. Response variables were considered in relation to two factors: WNS presence at MACA (pre-detection vs. post-detection), and prescribed fire (burned vs. unburned). I compared my response variables to the two listed factors by performing a two-factor ANOVA using the program ‘R’ v.3.1.2 (Peetor 2011; R Development Core Team 2012).

Results

Bat activity on MACA was recorded on 1,538 detector/nights across all years. A total of 7,595 passes (consisting of 91,158 pulses) were recorded; comprised of 1,102 low phonic passes (consisting of 13,591 pulses), 2,556 mid phonic passes (consisting of 32,208 pulses), and 3,937 *Myotis* phonic passes (consisting of 45,359 pulses). In total, 11 species of bats were identified in these surveys at MACA (Appendices 1-2).

The global model for low phonic bat activity on MACA was significant ($F_{3, 1534} = 11.06$, $P < 0.01$). Low phonic activity was greater in burned habitats; with a mean of 0.91 ± 0.17 (SE) low phonic passes per detector / night in burned habitats versus 0.27 ± 0.06 low phonic passes in unburned areas ($P < 0.01$). Low phonic activity increased from a mean of 0.37 ± 0.09 passes before the detection of WNS to 1.7 ± 0.39 low phonic passes after the detection of WNS ($P < 0.01$). The interaction of WNS and prescribed fire was not significant for low phonic activity ($P > 0.05$) (Figure 2.4).

The global model for mid phonic bat activity on MACA was significant ($F_{3, 1534} = 8.43$, $P < 0.01$). Mid phonic activity did not differ with regard to prescribed fire ($P > 0.05$), or the interaction of WNS with prescribed fire ($P > 0.05$); however, mid phonic activity decreased from a mean of 2.09 ± 0.19 passes before the detection of WNS to 0.16 ± 0.16 mid phonic passes after the detection of WNS ($P < 0.01$) (Figure 2.5).

The global model was significant for *Myotis* phonic activity ($F_{3, 1534} = 33.4$, $P < 0.01$) on MACA. The effects of prescribed fire and WNS were significant for *Myotis* phonic activity ($P < 0.01$). There was a significant interaction between WNS and prescribed fire for the *Myotis* phonic group ($P < 0.01$). Before the detection of WNS,

Myotis activity was less in burned habitats (2.08 ± 0.19 mean number of passes) than unburned habitats (6.49 ± 0.91 mean number of passes). After the detection of WNS, *Myotis* activity was greater in burned habitats (0.25 ± 0.10 mean number of passes) than unburned habitats (0.007 ± 0.007 mean number of passes) (Figure 2.6).

Insect abundance on MACA was sampled for 414 trap/nights across all years. A total of 285,804 insects were collected; Lepidoptera (85,302), Coleoptera (58,441), Diptera (56,193), other insect orders (84,595), and unidentified insects (1,693) (Appendix 3). The global model for total insect abundance in malaise traps was not significant ($F_{3, 393} = 1.97$, $P > 0.05$) (Figure 2.7). The global model for Lepidoptera captured in blacklight traps was significant ($F_{3, 414} = 19.65$, $P < 0.01$); Lepidoptera were more abundant after WNS and in unburned areas ($P < 0.01$) (Figure 2.8). There was no interaction between prescribed fire and WNS for Lepidoptera ($P > 0.5$). The global model for Coleoptera captured in blacklight traps was significant ($F_{3, 414} = 7.7$, $P < 0.01$); Coleoptera were more abundant after WNS and in burned areas ($P < 0.05$) (Figure 2.9). There was no interaction between prescribed fire and WNS for Coleoptera ($P > 0.05$). The global model for Diptera captured in blacklight traps was not significant ($P > 0.05$) (Figure 2.10).

Discussion

This study provides novel, community-level data regarding response of various phonic groups of bats to prescribed fire and WNS. These results provide evidence that prescribed fire impacts bat activity across the landscape of MACA, and that WNS has had an interacting effect on the shift in habitat use for some phonic groups of bats. The greatest change in activity observed was for the *Myotis* phonic group, which significantly declined in activity across the landscape in the years following detection of WNS in MACA. However, I found the use of burned habitats was greater than unburned habitats by *Myotis* bats after the arrival of WNS. Activity of open-space foragers, e.g. *L. cinereus*, *L. noctivagans*, and *E. fuscus* increased, presumably from the decreased activity of mid- and *Myotis*-phonic bat species (Dzal et al. 2011; Jachowski et al. 2014). Ford et al. (2011) observed declines in activity of multiple *Myotis* species after the arrival of WNS in New York State in the year following detection of WNS at their site; however they observed no change in activity for *E. fuscus*, *L. borealis*, or *P. subflavus*. This study demonstrated that WNS had immediate impacts on species that do not suffer from the disease, e.g. *L. cinereus*, *L. noctivagans*, *E. fuscus*, *L. borealis*, and *N. humeralis*. I postulate that WNS altered the bat community as a whole at MACA, not just through mortality of bats in the genus *Myotis*, but also through competitive release of other bat species.

Open-space foragers in this study used burned habitats more than unburned habitats. This is in agreement with the morphological characteristics of open-space foragers. Prescribed fire decreases the amount of clutter in the mid- and under-story of eastern deciduous forests (Arthur et al. 2012; Perry 2012; Cox et al. 2016). Open-space

foragers would likely use habitats with open canopies and reduced amounts of clutter, as these bats can maintain higher flight speeds and encounter less echolocation interference (Adams et al. 2009; Müller et al. 2012). Activity of open-space foragers increased in this study after the detection of WNS, likely due to decreased competition from other phonic groups.

Mid phonic group bats on MACA, i.e., *P. subflavus*, *L. borealis*, and *N. humeralis*, did not display the degree of use of burned habitats as did open-space foragers. This phonic group is tolerant of increasing amounts of clutter (Brooks 2009). Assuming mid phonic group bats can forage efficiently in open and closed canopies, these species likely transition between burned and unburned habitats to locate abundant prey. While I observed no change in habitat use, there was a decline in overall activity of mid-phonic bats after the detection of WNS. I believe the decline of mid phonic bat activity is likely attributed to the mortality of *P. subflavus*, a cave hibernating, WNS-impacted species (Foley et al. 2011; Alves et al. 2014). Since the detection of WNS, populations of impacted *Myotis* species and *P. subflavus* have declined on MACA (Lacki et al. 2015; Thomas 2016). The temporal drop in activity for the mid phonic bat group was not as dramatic as for the *Myotis* phonic group. I believe this difference is due to the two mid-phonic species (*N. humeralis* and *L. borealis*) that occur on MACA being species which are not cave-hibernators and, therefore, less prone to WNS-related mortality.

I found an interaction between prescribed fire and WNS for the *Myotis* phonic group on MACA. Before the arrival of WNS, *Myotis* species used unburned habitats

more than burned habitats, presumably because *Myotis* species are tolerant of clutter (Norberg and Rayner 1987; Bergeson et al. 2013; Silvis et al. 2016). Their wing morphology allows for a high degree of maneuverability and their echolocation call characteristics are suited to detecting a greater amount of obstacles over a shorter distance (Thomson 1982; Caceres and Barclay 2000). I postulate that WNS infected bats emerging from hibernation with lowered body mass and impaired wing function will likely use areas for foraging that are least energetically expensive and that require less flight maneuverability (Cryan et al. 2010; Lacki et al. 2015). Fuller et al. (2011) found that *M. lucifugus* with high levels of wing damage from WNS had impaired body conditions and likely suffered repeated damage from exposure to the fungus across multiple hibernation periods. I suggest that *Myotis* bats foraging in burned habitats would have less energetic costs associated with foraging in more open canopy structures. Results from this study also indicated a greater abundance of Coleoptera in burned habitats, which would facilitate *Myotis* species foraging success.

Results for this study are consistent with previous findings concerning the responses of bats to prescribed fire; burned habitats had greater bat activity, and open-space foragers had a more dramatic response than *Myotis* species (Loeb et al. 2008; Cox et al. 2016). Most research is in agreement that foraging bats respond positively to prescribe fire because of a decrease in canopy clutter (Boyles and Aubrey 2006; Lacki et al. 2009; Perry 2012; Silvis et al. 2016). Given that WNS has caused a drastic decline in some cave-hibernating species (Frick et al. 2010; Foley et al. 2011; Thogmartin et al. 2012; USFWS 2015a), my results are consistent with other acoustic surveys that demonstrate declines in activity of WNS-impacted species, with either no change or an

increase in activity levels of bat species not susceptible to WNS (Brooks 2011; Dzal et al. 2011; Coleman and Reichard 2014).

Acoustic monitoring of bats has limitations and assumptions that must be acknowledged (Loeb and Waldrop 2008). Quality and quantity of echolocation calls are affected by the amount of obstruction from vegetation in front of the microphone (Britzke et al. 2010; Kaiser and O’Keefe 2015). Acoustic detectability of bats is reduced for species with low amplitude echolocation, e.g. *M. septentrionalis* and *Corynorhinus rafinesquii*; thus, acoustic surveys can often under-represent activity levels of some species (Loeb and Waldrop 2008; Agranat 2012; Frick 2013). When using an automated classifier, some calls may be misidentified or not recognized (Lemen et al. 2015; Russo and Voigt 2016). Never-the-less, my data span more than half a decade of monitoring and provide at least a relative indicator of bat activity across MACA because the same methods were used across all years.

The relationship between abundance of insect prey and prescribed fire is equivocal. Some studies have found that prescribed fire does not impact insect abundance (Swengel 2001; Cox et al. 2016), while others have indicated prescribed fire leads to increases in the abundance of some insect groups [i.e., Lepidoptera, Coleoptera, and Diptera (Lacki et al. 2009; Perry 2012)]. I observed an increase in the total abundance of insect prey on MACA, presumably due to the dramatic decrease in *Myotis* activity following the arrival of WNS. I postulate insect populations likely increased, in part, due to decreased predation by *Myotis* species.

All phonic groups of bats on MACA used prescribed burns more after arrival of WNS, suggesting these habitats are of importance for sustaining populations of foraging bats vulnerable to WNS. Conservation efforts for WNS-impacted species are especially important now due to the drastic decline in population numbers of susceptible bat species. While my data demonstrate community-wide changes in bat activity since the detection of WNS, further research and monitoring is needed to determine if open-space foragers fill the ecological niche and that *Myotis* phonic group once served on MACA.

Conclusions

As I hypothesized, low phonic bat species were more active in burned areas, which is in agreement with the morphological characteristics of the low phonic group. My hypothesis that mid phonic group activity would be greater in burned areas was not supported, presumably because mid phonic species are variable in where they forage. My hypothesis that low phonic activity increased after WNS was supported, likely from reduced competition, but was not supported for mid phonic group activity. Mid phonic activity decreased after WNS, potentially from the population decline of *P. subflavus* due to WNS. The results supported my hypothesis that the activity of the *Myotis* phonic group declined after WNS in burned and unburned habitat, since these species are heavily impacted by WNS. The abundance of insects did increase after WNS, supporting my hypothesis. These data indicate an increase in abundance of some insects after prescribed burns, potentially increasing prey availability for foraging bats (Dodd et al 2012; Lacki et al. 2009; Perry 2012). Research has indicated that prescribed fire decreases the amount of clutter in the canopy, which may provide more efficient foraging for all phonic groups

(Perry 2011; Silvis 2016). Managers implementing prescribed fire regimes for silvicultural practices can take into consideration the positive effects of prescribed fire for foraging bats, particularly species suffering from WNS. Prescribed burns that take place at regular intervals, maintain lower levels of clutter in the canopy (Boyles and Aubrey 2006; Dickinson et al. 2009; Perry 2011). Prescribed fire is a versatile silvicultural tool which can additionally be used to manage a forest for foraging bat species.

Chapter 3

Habitat use by *Myotis sodalis* and *Myotis septentrionalis* on Mammoth Cave National Park in relation to landscape characteristics

Introduction

The disease, White-nose Syndrome (WNS), has resulted in population declines of many cave-hibernating bat species (USFWS 2015a). Given coincidental observed shifts in bat communities (Moosman et al. 2013; Francl et al. 2012; Jachowski et al. 2014), it is critical to determine the habitat use of persistent bat species. Two federally listed cave hibernating species of interest are *Myotis sodalis* (Indiana bat) and *Myotis septentrionalis* (northern long-eared bat). Generally, habitat use by insectivorous bats is influenced by distance from edges, location in relation to riparian areas, and structural conditions of forest canopies (Krusic et al. 1996; Schirmacher et al. 2007). Loeb and O'Keefe (2006) found in the southeastern U.S. bat habitat use was greatest in forest stands that were at an early-successional stage and had the least amount of clutter. Schimacher et al. (2007) showed that areas closer to riparian corridors were used more by bats than upland areas. While *M. sodalis* and *M. septentrionalis* use habitats with these characteristics, research has shown additional habitat features can influence their habitat use (Yates and Muzika 2006; Foster and Kurta 1999; De La Cruz and Ward 2016; Brack 2006).

Broadly, *M. sodalis* and *M. septentrionalis* share similar morphological features. These species have high-echolocation call structures and wing shape adapted for foraging in relatively cluttered forest canopies (Harvey et al. 1999; Reid 2006; Jantzen and Fenton

2013); hence, they use habitats with similar qualities. Areas that are known to be utilized by both *M. sodalis* and *M. septentrionalis* are comprised of large intact forests (Yates and Muzika 2006; Schirmacher et al. 2007; Silvis et al. 2016). Menzel et al. (2005) reported that *M. sodalis* use areas of closed canopy forest more than open grasslands or agricultural areas. Owen et al. (2003) found that in West Virginia, intact forests were used the most by female *M. septentrionalis*. Both *M. sodalis* and *M. septentrionalis* can utilize riparian corridors in closed forest canopies (Miller et al. 2003; Murray and Kurta 2004; Sparks et al. 2005). These species avoid highly developed areas and will only use agricultural areas if there are forest edges or patches within the agricultural mosaic (Krusic et al. 1996; Menzel et al. 2005). To-date, *M. sodalis* and *M. septentrionalis* have experienced dramatic population declines resulting from WNS, and determining suitable management areas for these federally-listed species is essential. Mammoth Cave National Park (MACA) represents an important site for these species because large numbers of *M. sodalis* and *M. septentrionalis* because large number of both species hibernate in the caves in the area (Lacki et al. 2015; Thomas 2016). Furlonger et al. (1987) found that *Myotis* species were more concentrated in areas closer to hibernaculum. Determining features of habitats used by *M. sodalis* and *M. septentrionalis*, particularly near hibernaculums of these species, could aiding in management planning.

Local landscape characteristics may contribute to *M. sodalis* and *M. septentrionalis* habitat use. Research has shown that forest stand level characteristics (plant composition, canopy closure, and basal area) influence habitat use (Ford et al. 2006; Loeb and O’Keefe 2006; Owen et al. 2013). Many research has examined bat use of habitats where silvicultural practices have been employed (e.g., Loeb and O’Keefe

2006; Loeb and Waldrop 2008; Lacki et al. 2012). However, few studies have looked at how bats use forests that have been subjected to prescribed fire. Since fire alters the structure of forest canopies, it can have an effect on how bats use burned habitats (Boyles and Aubrey 2006; Dickinson et al. 2009; Johnson et al. 2010).

MACA has employed a prescribed fire regime since 2002 to manage its forests (NPS 2001). Populations of *M. sodalis* and *M. septentrionalis* have been declining in the park since the detection of WNS in January 2013 (Griffitts et al. 2016; NPS 2013). The objective of this study was to document habitat use by *M. sodalis* and *M. septentrionalis* on MACA in relation to forest characteristics, local spatial characteristics, and prescribed fire. I hypothesized that *M. sodalis* and *M. septentrionalis* habitat use will be influenced most by landscape characteristics (i.e., distance from water and distance from edges).

Study Area

Mammoth Cave National Park is a 23,000-ha parcel of land located in Edmondson County with small portions in Barren and Hart counties. MACA is on the edge of the Crawford-Mammoth Cave Uplands of the Interior Plateau of Kentucky, encompasses the longest cave system in the world, and is bisected by the Green River (NPS 2001; Woods et al. 2002). MACA is a karst landscape, with an annual mean precipitation of 107-130 cm, a mean low temperature of -6°C in January, and a mean high temperature of 33°C in July (Woods et al. 2002). A fire management plan was implemented with the goal to “...maintain and restore ecological processes that existed before settlement within the park lands...” (NPS 2001, p. 19). Seven burn units across a

variety of habitats in MACA were established; with burns taking place since 2002 (Figure 2.1 – 2.2). Deciduous, oak-hickory forests located on upland ridges are composed of white oak (*Quercus alba*), black oak (*Q. velutina*), southern red oak (*Q. falcata*), pignut hickory (*Carya glabra*), and post oak (*Q. stellata*) (NPS 2011). Mesic areas are composed of maple (*Acer spp.*), white ash (*Fraxinus americana*), and yellow poplar (*Liriodendron tulipifer*); riparian areas have sweet gum (*Liquidambar styraciflua*), red maple (*Acer rubrum*), sycamore (*Platanus occidentalis*), birch (*Betula spp.*), and hackberry (*Celtis spp.*) (Woods et al. 2002).

Methods

Acoustic Sampling

I monitored bat activity using full-spectrum acoustic detectors, Songmeter SM3 (“Bat+” option, Wildlife Acoustics Inc., Maynard, MA) from April to September during 2015 and 2016. All detectors were regularly calibrated to minimize variation between detectors. Detectors were housed in plastic cases (Pelican Products, Torrance, CA, Model #1500) to protect them from inclement weather conditions; microphones were suspended 3.0 m above ground and oriented towards the most open space in the canopy (Fulton et al. 2014; Appendix 5). Detectors were deployed in randomly established transects (n = 12) within each burn unit and a corresponding unburned control unit (n = 5), which have no history of prescribed fire (Figure 3.1) (Dodd et al. 2013). Transects composed of two detectors deployed 200 m apart, starting from the exterior of the site proceeding to the interior (Figure 3.1). Acoustic surveys spanned multiple consecutive nights to account for

nightly variation of bat activity throughout the growing season. Detectors were operated in at least one or more burn sites and one or more unburned sites simultaneously during a monitoring session to account for spatial variation.

Kaleidoscope Pro v.1.2 (Wildlife Acoustics, Maynard, MA), was used to download acoustic data (zero-crossing format). Echolocation sequences containing ≥ 5 pulses were quantified as “passes” (series of pulses at the same point in time) and identified to species using the reference library of Kaleidoscope Pro v.3.1.4B (Wildlife Acoustics, Maynard, MA). Only passes with a positive species identification for were used in the analysis.

Habitat Characteristics

Detector points were recorded using a Global Positioning System (GPS). I determined canopy closure and basal area at each detector point and 3 m in each cardinal direction using a densiometer (Forestry Suppliers, Inc., Jackson, MS) and factor-10 wedge prism (Forestry Suppliers, Inc., Jackson, MS), respectively. Detector points were overlaid on Geographic Information System (GIS) layers of MACA and analyzed spatial data in ArcMap 10.1 (ESRI, Redlands, California). Data layers included: streams, the Green River, roads, trails, and MACA fire history. For each point I extracted the distance to the nearest: flowing water, trail, and road using the Near tool in ArcMap (Allen 2010).

Statistical Analysis

I used multiple linear regression paired with Akaike’s Information Criterion (AIC) model ranking to determine the most parsimonious model for predicting *M. sodalis*

and *M. septentrionalis* activity based on habitat characteristics. I developed three *a priori* models which focused on stand characteristics, burn characteristics, and landscape characteristics. Predictor variables for the stand model included canopy closure and basal area. Predictor variables for the burn model were burn presences (burned or unburned), years since burn, and burn frequency. Predictor variables for the landscape model were distance to road and trail, distance to flowing water, aspect, and elevation. I used AIC differences relative to smallest AIC values (Δ AIC) and AIC weights (w_i) to assess the suitability of habitat models (Burnham and Anderson 2002; Lacki et al. 2012). For models with strong support, I examined significant estimate parameters ($P \leq 0.05$) to determine the best variables for predicting the activity of *M. sodalis* and *M. septentrionalis*, respectively.

Results

A total of 266 detector / nights were surveyed across 33 detector locations on MACA. I recorded a total of 5,422 passes (consisting of 89,002 pulses); of those 162 were *M. sodalis* (consisting of 2,397 pulses) and 247 were *M. septentrionalis* (consisting of 3,613 pulses). The only significant model was the landscape model (Table 3.1). Parameter estimates were significant for aspect in the landscape model for *M. sodalis*, suggesting a negative relationship between *M. sodalis* activity and aspect. No parameter estimates were significant in the landscape model for *M. septentrionalis* (Table 3.2).

Discussion

Modelling efforts in this study indicated that landscape characteristics were the best variables for explaining *M. sodalis* and *M. septentrionalis* habitat use. Research has implicated landscape characteristics to be the best explaining variables for *M. sodalis* and *M. septentrionalis* habitat use (Ford et al. 2005; Ford et al. 2006; De La Cruz and Ward 2016). Of the landscape characteristics, aspect was negatively related to *M. sodalis* activity but not *M. septentrionalis* activity. This is in contrast to the results of De La Cruz and Ward (2016), who reported aspect did not impact the activity of *M. sodalis* in West Virginia.

The number of sampling points during this study was small for modelling bat habitat use. Since the arrival of WNS to MACA, populations of *M. sodalis* and *M. septentrionalis* have declined; possibly reducing the acoustic detectability of the species across MACA's landscape (Lacki et al. 2015; Griffitts et al. 2016). In addition, *M. septentrionalis* echolocate at lower amplitudes, potentially resulting in lower detection rates (Sherwin et al. 2000). Detectability issues, and that my models do not include all habitat variables which could impact bat species, limited the conclusions I could draw.

Additional research designed to obtain the data needed to better model the habitat features of importance to *M. sodalis* and *M. septentrionalis* at MACA is needed. Research has implicated the importance of stand and prescribed burn features in addition to landscape features (Dodd et al. 2016; Loeb and O'Keefe 2006). However, until this information is available, I recommend that aspect be incorporated into the suite of factors

considered by managers at MACA as management plans are developed for bats which incorporate prescribed burning.

Literature Cited

- Adams, R.A. and K.M. Thibault. 2006. Temporal resource partitioning by bats at water holes. *Journal of Zoology*, 270, 466–472.
- Adams, M.D., B.S. Law, and K.O. French. 2009. Vegetation structure influences the vertical stratification of open- and edge-space aerial-foraging bats in harvested forests. *Forest Ecology and Management*, 258, 2090–2100.
- Agranat, I. 2012. Bat species identification from zero crossing and full spectrum recordings with new techniques using HMMs and Fisher Scores. *Bat Research News*, 53, 62.
- Aldridge, H.D.J.. and I.L. Rautenbach. 1988. Morphology, echolocation and resource partitioning in insectivorous bats. *Journal of Animal Ecology*, 56, 763–778.
- Allen, D.W. 2010. *GIS Tutorial 2: Spatial Analysis Workbook*. Esri Press, Redlands, California.
- Altringham, J.D. 2011. *Bats : From Evolution to Conservation*, Second. Oxford University Press, New York, New York.
- Alves, D.M.C.C., L.C. Terribile, and D. Brito. 2014. The potential impact of white-nose syndrome on the conservation status of North American bats. *PloS one*, 9, e107395.
- Arthur, M.A., H.D. Alexander, D.C. Dey, C.J Schweitzer, and D.L. Loftis. 2012. Refining the oak – fire hypothesis for management of oak-dominated forests of the eastern United States. *Journal of Forestry*, 5, 257–266.

- Barbour, R.W. and W.H. Davis. 1969. *Bats of America*. University Press of Kentucky, Lexington, Kentucky.
- Bergeson, S.M., T.C. Carter, and M.D. Whitby. 2013. Partitioning of foraging resources between sympatric Indiana and little brown bats. *Journal of Mammalogy*, 94, 1311–1320.
- Borror, D.J. and R.E. White. 1970. *Peterson's Field Guide : Insects*. Houghton Mifflin Harcourt Publishing Company, New York, New York.
- Boyles, J.G., P.M. Cryan, G.F. McCracken, and T.K. Kunz. 2011. Economic importance of bats in agriculture. *Science* 332: 41–42.
- Boyles, J.G. and D.P. Aubrey. 2006. Managing forests with prescribed fire: Implications for a cavity-dwelling bat species. *Forest Ecology and Management*, 222, 108–115.
- Brack Jr, V. 2006. Autumn activity of *Myotis sodalis* (Indiana bat) in Bland County, Virginia. *Northeastern Naturalist*, 13(3), 421–434.
- Britzke, E.R., J.E. Duchamp, K.L. Murray, R.K. Swihart, and L.W. Robbins. 2011. Acoustic identification of bats in the eastern United States: A comparison of parametric and nonparametric methods. *Journal of Wildlife Management*, 75(3), 660–667.
- Britzke, E.R., B.A. Slack, M.P. Armstrong, and S.C. Loeb. 2010. Effects of orientation and weatherproofing on the detection of bat echolocation calls. *Journal of Fish and Wildlife Management*, 1, 136–141.
- Brooks, R.T. 2011. Declines in summer bat activity in central New England 4 years following the initial detection of white-nose syndrome. *Biodiversity and Conservation*, 20, 2537–2541.

- Brooks, R.T. 2009. Habitat-associated and temporal patterns of bat activity in a diverse forest landscape of southern New England, USA. *Biodiversity and Conservation*, 18, 529–545.
- Brose, P., T. Schuler, D. Van Lear, and J. Berst. 2001. Bringing fire back: the changing regimes of the Appalachian mixed-oak forests. *Journal of Forestry*, 99(11), 30-35.
- Buchalski, M.R., J.B. Fontaine, P.A. Heady, J.P. Hayes, and W.F. Frick. 2013. Bat response to differing fire severity in mixed-conifer forest California, USA. *PloS one*, 8, e57884.
- Burnham, K.P. and D.R. Anderson. 2002. *Model selection and multi-model inference*. Springer, New York, New York.
- Burton, J.A. 2013. Effects of prescribed fire on Mammoth Cave National Park’s oak-hickory vegetation : A decade of fire monitoring. Pp 163 – 170 in *Proceedings of Mammoth Cave National Park’s 10th Research Symposium* (S. R. Trimboli, editor). Mammoth Cave National Park, Mammoth Cave, Kentucky.
- Caceres, M.C. and R.M.R Barclay. 2000. *Myotis septentrionalis*. *Mammalian Species*, 634, 1–4.
- Coleman, J.T.H. and J.D. Reichard. 2014. Bat White-nose Syndrome in 2014: A brief assessment seven years after discovery of a virulent fungal pathogen in North America. *Outlooks on Pest management*, 25, 374–377.
- Coleman, L.S., W.M. Ford, C.A. Dobony, and E.R. Britzke. 2014. A comparison of passive and active acoustic sampling for a bat community impacted by White-nose Syndrome. *Journal of Fish and Wildlife Management*, 5(1): 1–24.

- Cox, M.R., E.V. Willcox, P.D. Keyser, and A.L. Vander Yacht. 2016. Bat response to prescribed fire and overstory thinning in hardwood forest on the Cumberland Plateau, Tennessee. *Forest Ecology and Management*, 359, 221–231.
- Cryan, P.M., C.U. Meteyer, J.G. Boyles, and D.S. Blehert. 2010. Wing pathology of White-nose Syndrome in bats suggests life-threatening disruption of physiology. *BMC biology*, 8, 135.
- Davis, W.H. 1974. *Mammals of Kentucky*. University Press of Kentucky, Lexington, KY.
- De La Cruz, J.L. and R.L. Ward. 2016. Summer-Habitat Suitability Modeling of *Myotis sodalis* (Indiana Bat) in the Eastern Mountains of West Virginia. *Northeastern Naturalist* 23:100–117.
- Dickinson, M.B., M.J. Lacki, and D.R. Cox. 2009. Fire and the endangered Indiana bat. Pp. 51-75 in *Proceedings of the 3rd Fire in Eastern Oak Forests Conference* (T. F. Hutchinson, editor), Carbondale, Illinois.
- Dodd, L.E., N.S. Skowronski, M.B. Dickinson, M.J. Lacki, and L.K. Rieske. 2013. Using LiDAR to link forest canopy structure with bat activity and insect occurrence: preliminary findings. Pp. 50-57 in *Proceedings of Mammoth Cave National Park's 10th Research Symposium* (S. R. Trimboli, editor). Mammoth Cave National Park, Mammoth Cave, Kentucky.
- Dodd, L.E., M.J. Lacki, E.R. Britzke, D.A. Buehler, P.D. Keyser, J.L. Larkin, A.D. Rodewald, T.B. Wigley, P.B. Wood, and L.K. Rieske. 2012. Forest structure affects trophic linkages: How silvicultural disturbance impacts bats and their insect prey. *Forest Ecology and Management*, 267, 262–270.

- Dzal, Y., L.P. McGuire, N. Veselka, and M.B. Fenton. 2011. Going, going, gone: The impact of white-nose syndrome on the summer activity of the little brown bat (*Myotis lucifugus*). *Biology letters*, 7(3), 392–394.
- Fenton, M.B. 2012. Bats and White-nose Syndrome. *Proc Natl Acad Sci USA*, 109, 6794–6795.
- Foley, J., D. Clifford, K. Castle, P. Cryan, and R.S. Ostfeld. 2011. Investigating and managing the rapid emergence of White-nose Syndrome, a novel, fatal, infectious disease of hibernating bats. *Conservation Biology*, 25(2), 223-231.
- Ford, W.M., E.R. Britzke, C.A. Dobony, J.L. Rodrigue, and J.B. Johnson. 2011. Patterns of acoustical activity of bats prior to and following white-nose syndrome occurrence. *Journal of Fish and Wildlife Management*, 2(2), 125-134.
- Ford, W.M., J.M. Menzel, M.A. Menzel, J.W. Edwards and C. Kilgo. 2006. Presence and absence of bats across habitat scales in the upper coastal plain of South Carolina. *The Journal of Wildlife Management* 70:1200–1209.
- Ford, W.M., M.A. Menzel, J.L. Rodrigue, J.M. Menzel and J.B. Johnson. 2005. Relating bat species presence to simple habitat measures in a central Appalachian forest. *Biological Conservation*:582–539.
- Foster, R.W. and A. Kurta. 1999. Roosting ecology of the northern bat (*Myotis septentrionalis*) and comparisons with the endangered Indiana bat (*Myotis sodalis*). *Journal of Mammology*, 80(2), 659-672.
- Francel, K.F., W.M. Ford, D.W. Sparks, and V. Brack Jr. 2012. Capture and reproductive trends in summer bat communities in West Virginia: Assessing the impacts of White-nose Syndrome. *Journal of Fish and Wildlife Management*, 3(1), 33-42.

- Frank, C.L., A. Michalski, A.A. McDonough, M. Rahimian, R.J. Rudd, and C. Herzog. 2014. The resistance of a North American bat species (*Eptesicus fuscus*) to White-nose Syndrome (WNS). PloS one, 9, e113958.
- Frick, W.F. 2013. Acoustic monitoring of bats, considerations of options for long-term monitoring. Therya, 4, 69–78.
- Frick, W.F., J.F. Pollock, A.C. Hicks, K.E. Langwig, D.S. Reynolds, G.G. Turner, C.M. Butchkoski, and T.H. Kunz. 2010. An emerging disease causes regional population collapse of a common North American bat species. Science, 329, 679–682.
- Fuller, N.W., J.D. Reichard, M.L. Nabhan, S.R. Fellows, L.C. Pepin, and T.H. Kunz. 2011. Free-ranging little brown myotis (*Myotis lucifugus*) heal from wing damage associated with white-nose syndrome. EcoHealth, 8(2), 154-162.
- Fulton, S.A., L.E. Dodd, and L.K. Rieske. 2014. Hydric habitats are important to foraging bats in the Bluegrass region's urban parks. Urban Naturalists, 3, 1-13.
- Furlonger, C.L., H.J. Dewar, and M.B. Fenton. 1987. Habitat use by foraging insectivorous bats. Can. J. Zool. 65(2): 284–288.
- Gargas, A., M.T. Trest, M. Christensen, T.J. Volk, and D.S. Blehert. 2009. *Geomyces destructans* sp. nov. associated with bat White-nose Syndrome. Mycotaxon, 108, 147–154.

- Griffitts, R.E., L.E. Dodd, and M.J. Lacki. 2016. The activity of *Myotis sodalis* and *Myotis septentrionalis* changes on the landscape of Mammoth Cave National Park following the arrival of White-nose Syndrome. Mammoth Cave National Park's 11th Research Symposium, Mammoth Cave National Park, KY, April 18-20, 2016.
- Harvey, M.J., J.S. Altenbach, and T.L. Best. 1999. *Bats of the United States*. Arkansas Game and Fish Commission, Arkansas.
- Hines, B. and M. Armstrong. 2014. Kentucky WNS Response Plan updated January 2014.
<http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1452&context=usfwspubs>. Accessed January 2015.
- Holderied, M.W. and O. von Helversen. 2003. Echolocation range and wingbeat period match in aerial-hawking bats. *Proceedings of the Royal Society B: Biological Sciences*, 270, 2293–2299.
- Jachowski, D.S., C.A. Dobony, L.S. Coleman, W.M. Ford, E.R. Britzke, and J.L. Rodrigue. 2014. Disease and community structure: White-nose Syndrome alters spatial and temporal niche partitioning in sympatric bat species. *Diversity and Distributions*, 20(9), 1002–1015.
- Jantzen, M.K. and M.B. Fenton. 2013. The depth of edge influence among insectivorous bats at forest-field interfaces. *Canadian Journal of Zoology*, 91, 287–292.
- Johnson J.B., W.M. Ford, J.L. Rodrigue, and C.M. Johnson. 2010. Roost selection by male Indiana *Myotis* following forest fires in central Appalachian hardwoods forests. *Journal of Fish and Wildlife Management*, 1(2), 111-121.

- Kaiser, Z.D.E. and J.M. O’Keefe. 2015. Data acquisition varies by bat phonic group for 2 types of bat detectors when weatherproofed and paired in field settings. *Wildlife Society Bulletin*, 39, 635–644.
- Krusic, R.A., M. Yamasaki, C.D. Neefus, and P.J. Pekins. 1996. Bat habitat use in White Mountain National Forest. *Journal of Wildlife Management*, 60(3), 625-631.
- Lacki, M.J., L.E. Dodd, R.S. Toomey, S.C. Thomas, Z.L. Couch, and B.S. Nichols. 2015. Temporal changes in body mass and body condition of cave-hibernating bats during staging and swarming. *Journal of Fish and Wildlife Management*, 6(2), 360-370.
- Lacki, M.J., M.D. Baker, and J.S. Johnson. 2012. Temporal dynamics of roost snags of long-legged *Myotis* in the Pacific Northwest, USA. *Journal of Wildlife Management*, 76(6), 1310-1316.
- Lacki, M.J., D.R. Cox, L.E. Dodd, and M.B. Dickinson. 2009. Response of Northern bats (*Myotis septentrionalis*) to prescribed fires in Eastern Kentucky forests. *Journal of Mammalogy*, 90, 1165–1175.
- Lacki, M.J., K.A. Sybill, and M.D. Baker. 2007. Foraging ecology of bats in forests. In: Lacki, M.J., J.P. Hayes, and A. Kurta, editors. *Bats in Forests: Conservation and Management*. John Hopkins University Press. Baltimore, Maryland. p. 83 – 127.
- Law, B., K.J. Park, and M.J. Lacki. 2016. Insectivorous bats and silviculture: balancing timber production and bat conservation. In: Voigt, C.C. and T. Kingston, editors. *Bats in the Anthropocene: Conservation of Bats in a Changing World*. Springer International Publishing, London, UK. p. 105 –150.

- Lemen, C., P. Freeman, J.A. White, and B.R. Andersen. 2015. The problem of low agreement among automated identification programs for acoustical surveys of bats. *Western North American Naturalist*, 75, 218–225.
- Loeb, S. and T. Waldrop. 2008. Bat activity in relation to fire and fire surrogate treatments in southern pine stands. *Forest Ecology and Management*, 255, 3185–3192.
- Loeb, S. and J.M. O’Keefe. 2006. Habitat use by forest bats in South Carolina in relation to local, stand, and landscape characteristics. *Journal of Wildlife Management*, 70(5), 1210-1218.
- Menzel, J M., W.M. Ford, M.A. Menzel, T.C. Carter, J.E. Gardner, J.D. Garner, and J.E. Hofmann. 2005. Summer habitat use and home-range analysis of the endangered Indiana bat. *Journal of Wildlife Management*, 69(1), 430-436.
- Miller, D.A., E.B. Arnett, and M.J. Lacki. 2003. Habitat management for forest-roosting bats of North America: A critical review of habitat studies. *Wildlife Society Bulletin*, 31(1), 30-44.
- Moosman, P.R., J.P. Veilleux, G.P. Pelton and H.H. Thomas. 2013. Changes in capture in a community of bats in New Hampshire during the progression of White-nose Syndrome. *Northeastern Naturalist*, 20(4), 552-558.
- Müller, J., M. Mehr, C. Bässler, M.B. Fenton, T. Hothorn, H. Pretzsch, H.J. Klemmt, and R. Brandl. 2012. Aggregative response in bats: Prey abundance versus habitat. *Oecologia*, 169, 673–684.
- Murray, S.W. and A. Kurta. 2004. Nocturnal activity of the endangered Indiana bat (*Myotis sodalis*). *Journal of Zoology*, 262, 197-206.

- National Park Service (NPS). 2013. Mammoth Cave National Park News Release: White-nose Syndrome confirmed in Park bats [Press Release]. Retrieved from https://www.whitenosesyndrome.org/sites/default/files/files/nr_-_maca_wns_announcement_-_final.pdf. Accessed February 2, 2016.
- National Park Service (NPS). 2012. White-nose Syndrome response plan. https://www.whitenosesyndrome.org/sites/default/files/http___www.nps_.gov_macaca_parkmgmt_loader.pdf. Accessed December 1, 2015.
- National Park Service (NPS). 2011. White-nose Syndrome response plan. Mammoth Cave National Park, Kentucky. <http://www.nps.gov/macal/learn/management/loader.cfm?csModule=security/getfileandPageID=330269>. Accessed February 4, 2015.
- National Park Service (NPS). 2001. Mammoth Cave National Park fire management plan December 2001. <http://www.nps.gov/macal/learn/management/upload/Fire%20Management%20Plan2001.pdf>. Accessed February 3, 2015.
- Norberg, U.M. and J.M.V Rayner. 1987. Ecological morphology and flight in bats (*Mammalia ; Chiroptera*): Wing adaptations, flight performance, foraging strategy and echolocation. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 316, 335–427.
- Owen, S.F., M.A. Menzel, W. M. Ford, B.R. Chapman, K.V. Miller, J.W. Edwards, and P.B. Wood. 2003. Home-range size and habitat used by the Northern *Myotis* (*Myotis septentrionalis*). The American Midland Naturalist, 2(150), 352-359.
- Peetor, T. 2011. *R Cookbook*. O'Reilly Media, Inc.

- Perry, R.W. 2011. A review of fire effects on bats and bat habitat in the eastern oak region. Proceedings of the 4th Fire in Eastern Oak Forest Conference; 2011 May 17-19 Springfield, MO, Gen Tech., 170–191.
- R Development Core Team. 2012. R: A language and environment for statistical computing. R Foundations for Statistical Computing, Vienna, Austria.
- Reeder, D.M., C.L. Frank, G.G. Turner, C.U. Meteyer, A. Kurta, E.R. Britzke, M.E. Vodzak, S.R. Darling, C.W. Stihler, A.C. Hicks, R. Jacob, L.E. Grieneisen, S.A. Brownlee, L.K. Muller, and D.S. Blehert. 2012. Frequent arousal from hibernation linked to severity of infection and mortality in bats with White-nose Syndrome. PLoS ONE, 7, e38920.
- Reid, F.A. 2006. *Peterson Field Guide to Mammals of North America*, Fourth. Houghton Mifflin Company, New York.
- Russo, D. and C.C. Voigt. 2016. The use of automated identification of bat echolocation calls in acoustic monitoring: A cautionary note for a sound analysis. Ecological Indicators, 66, 598–602.
- Schirmacher, M.R., S.B. Castleberry, W.M. Ford, and K.V. Miller. 2007. Habitat associations of bats in south-central West Virginia. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies, 61, 46-52.
- Schnitzler, H. and E.K.V. Kalko. 2001. Echolocation by insect-eating bats. BioScience, 51, 557.
- Sherwin, R.E., W.L. Gannon and S. Haymond. 2000. The efficacy of acoustic techniques to infer differential use of habitat by bats. Acta Chiropterologica 2:145–153.

- Silvis, A., R.W. Perry, and W.M. Ford. 2016. Relationships of three species of bats impacted by White-nose Syndrome to forest condition and management. U.S. Department of Agriculture, Southeastern Station, Asheville, North Carolina.
- Shumway, D.L., M.D. Abrams, and C.M. Ruffner. 2001. A 400-year history of fire and oak recruitment in an old-growth oak forest in western Maryland, USA. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, 31, 1437–1443.
- Southwood, T.R.E. 1987. *Ecological Methods*. Chapman and Hall, London, England.
- Sparks, D.W., C.M. Ritzi, J.E. Duchamp, and J.O. Whitaker. 2005. Foraging habitat of the Indiana bat (*Myotis sodalis*) at an urban–rural interface. *Journal of Mammalogy*, 86(4), 713-718.
- Swengel, A.B. 2001. A literature review of insects responses to fire, compared to other conservation managements of open habitat. *Biodiversity and Conservation*, 10, 1141-1169.
- Thogmartin, W.E., R.A. King, P.C. McKann, J.A. Szymanski, and L. Pruitt. 2012. Population-level impact of white-nose syndrome on the endangered Indiana bat. *Journal of Mammalogy*, 93, 1086–1098.
- Thomas, S.C. 2016. Recent winter bat numbers at Mammoth Cave National Park: Pre/Post white-nose syndrome arrival. Poster presented at: Southeastern Bat Diversity Network. 21st Annual Meeting and 26th Annual Colloquium on the Conservation of Mammals in Southeastern U.S. Feb 18-19; Lake Guntersville State Park, AL.
- Thomson, C.E. 1982. *Myotis sodalis*. *Mammalian Species*, 163, 1–5.

- Triplehorn, C.A. and N.F. Johnson. 2005. Borror and Delong's Introduction to the Study of Insects, seventh ed. Thomson Brooks/Cole, Belmont, California, USA, p. 888.
- United States Fish and Wildlife Service (USFWS). 2015a. White-nose Syndrome: The devastating disease of hibernating bats in North America.
http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1457&context=usfws_pubs. Accessed January 2016.
- United States Fish and Wildlife Service (USFWS). 2015b. Table 1. 2015 Population estimates for the Indiana bat (*Myotis sodalis*) by USFWS Region. U.S. Fish and Wildlife Service, Ecological Services Field Office, Bloomington, IN.
<https://www.fws.gov/midwest/Endangered/mammals/inba/pdf/2015IBatPopEstimate25Aug2015v2.pdf>. Accessed January 2015.
- United States Fish and Wildlife Service (USFWS). 2015c. Endangered and threatened wildlife and plants; threatened species status for the Northern long-eared bat with 4(d) Rule. 50 CFR Part 17. Federal Register, 80, 1–61.
- United States Fish and Wildlife Service (USFWS). 2011. A national plan for assisting States, federal agencies, and tribes in managing white-nose syndrome in bats.
http://static.whitenosesyndrome.org/sites/default/files/white-nose_syndrome_national_plan_may_2011.pdf. Accessed March 2016.
- United States Fish and Wildlife Service (USFWS). 2006. Indiana bat (*Myotis sodalis*) Draft Recovery Plan: first revision. U.S. Fish and Wildlife Service, Fort Snelling, MN, 237.

- Willis, C.K.R., A.K. Menzies, J.G. Boyles, and M.S. Wojciechowski. 2011. Evaporative water loss is a plausible explanation for mortality of bats from white-nose syndrome. *Integrative and Comparative Biology*, 51, 1 – 10.
- Woods, A.J., J.M. Omerik, W.H. Martin, G.J. Pond, W.M. Andrews, S.M. Call, J.A. Comstock, and D.D. Taylor. 2002. Ecoregions of Kentucky (color poster with map, descriptive text, summary tables, and photographs): Reston, VA., U.S. Geological Survey (map scale 1:1,000,000).
- Yates, M.D. and R.M. Muzika. 2006. Effect of forest structure and fragmentation on site occupancy of bat species in Missouri Ozark forests. *Journal of Wildlife Management*, 70(5), 1238-1248.
- Yela, J.L. and M. Holyoak. 1997. Effects of moonlight and meteorological factors on light and bait trap catches of noctuid moths. *Environmental Entomology*, 2: 1283-1290.

Table 1.1. Mean \pm SE passes per detector / night of the *Myotis* phonic group, *Myotis septentrionalis*, and *Myotis sodalis* at Mammoth Cave National Park prior to detection of White-nose syndrome (pre-WNS) (2010 – 2012) and following detection of White-nose Syndrome (post-WNS) (2013 – 2015).

Response Variable	Mean \pm SE Passes / Detector-Night		Test Significance
	Pre-WNS	Post-WNS	
<i>Myotis</i> phonic group	3.4 \pm 0.3	0.27 \pm 0.11	t _{1,344} = 9.6, P < 0.01
<i>Myotis septentrionalis</i>	0.60 \pm 0.09	0 \pm 0	t _{1,134} = 6.8, P < 0.01
<i>Myotis sodalis</i>	0.05 \pm 0.01	0.004 \pm 0.004	t _{1,379} = 4.9, P < 0.01

Table 3.1. Akaike's Information Criterion scores (AIC), differences in AIC values (Δ AIC), Akaike weights (w_i), and number of parameters (K) developed for multiple linear regression modeling activity of *Myotis sodalis* (Indiana bat) and *Myotis septentrionalis* (northern long-eared bat) using various habitat characteristics at Mammoth Cave National Park, 2015 – 2016. Models with an asterisk were significant ($P \leq 0.05$).

Response Variable	Model	AIC	Δ AIC	w_i	K
<i>M. sodalis</i> passes ($n = 162$)	Stand model	552.83	7.02	0.03	4
	Burn model	553.86	8.04	0.02	5
	Landscape model*	545.81	0	0.95	6
<i>M. septentrionalis</i> passes ($n = 247$)	Stand model	952.50	5.63	0.05	4
	Burn model	952.35	5.48	0.06	5
	Landscape model*	946.87	0	0.89	6

Table 3.2. Parameter estimates (β) and standard errors (SE) for habitat characteristics used in models of *Myotis sodalis* (Indiana bat) and *Myotis septentrionalis* (northern long-eared bat) activity (number of passes) at Mammoth Cave National Park, 2015 – 2016. Parameter estimates indicated by an asterisk were significant within a model ($P \leq 0.05$).

Model	Canopy Descriptor	Parameter Estimate (β) \pm SE	
		<i>M. sodalis</i> passes	<i>M. septentrionalis</i> passes
		Mean \pm SE	Mean \pm SE
Stand Model	Canopy Closure	0.062 \pm 0.06	0.13 \pm 0.13
	Basal Area	0.008 \pm 0.039 *	-0.040 \pm 0.084
Burn Model	Burn Presence	0.13 \pm 1.36	0.88 \pm 2.88
	Years since burn	0.00065 \pm 0.013	0.012 \pm 0.027
	Total number of burns	-0.42 \pm 0.47	-0.75 \pm 0.99
Landscape model	Distance to hard edge	-0.00068 \pm 0.002	-0.0012 \pm 0.0043
	Distance to flowing water	-0.00057 \pm 0.00069	0.0013 \pm 0.00145
	Aspect	-0.0052 \pm 0.0027 *	-0.0058 \pm 0.0044
	Elevation	0.014 \pm 0.0074	0.014 \pm 0.016

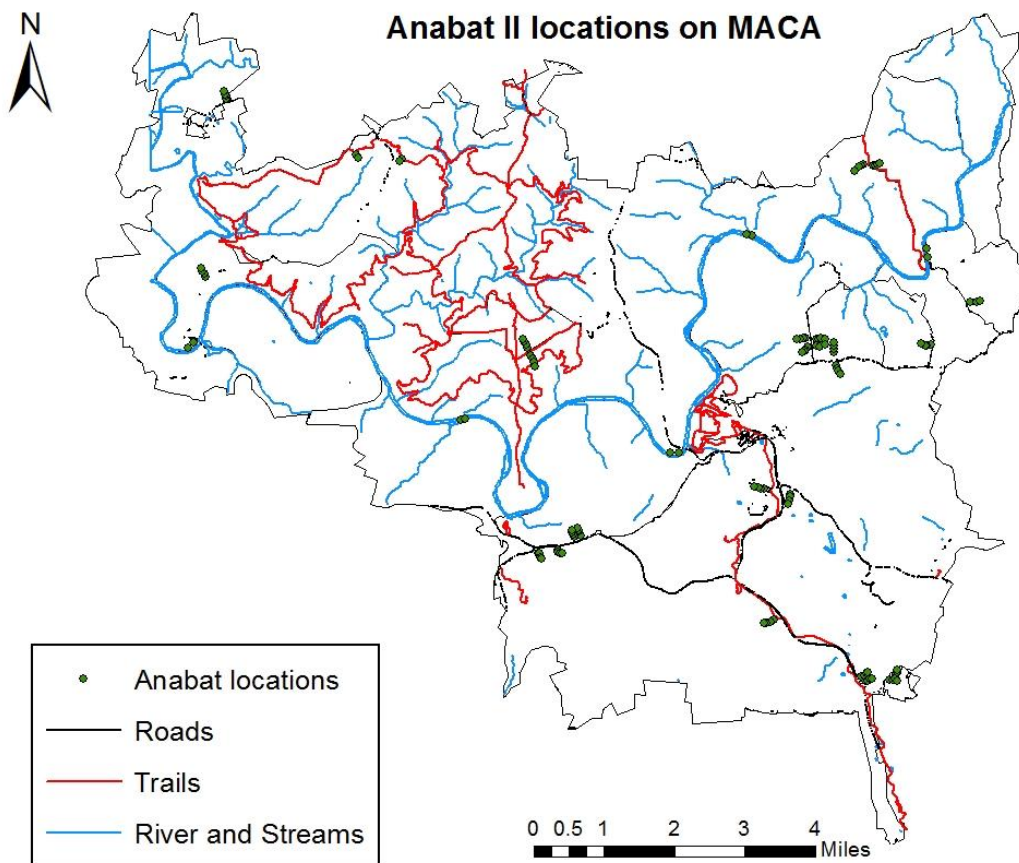


Figure 1.1. A map of Mammoth Cave National Park, including acoustic detector (Anabat II) locations ($n = 74$) used for bat activity monitoring from 2010 - 2015.

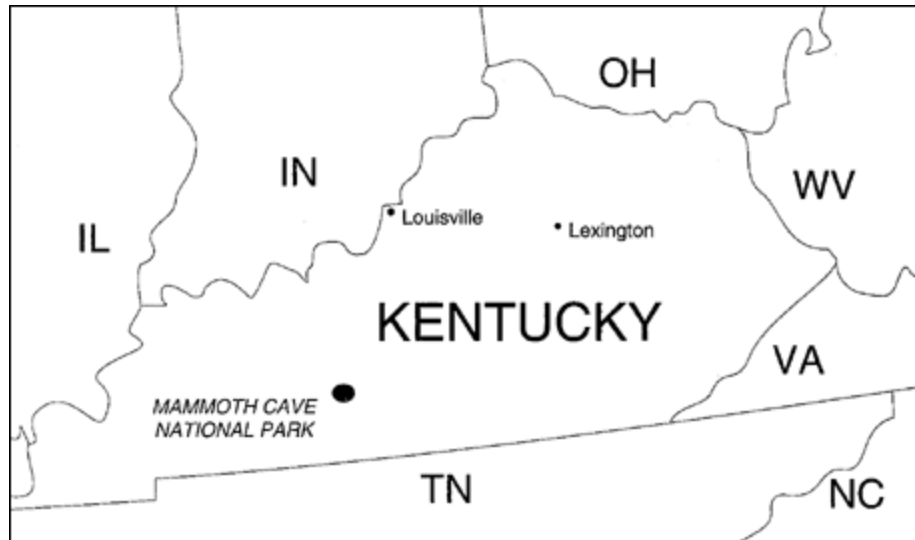


Figure 1.2. Location of Mammoth Cave National Park, Edmondson County, Kentuck, in relation to the southeast and Kentucky. Figure couresty of the National Park Service.

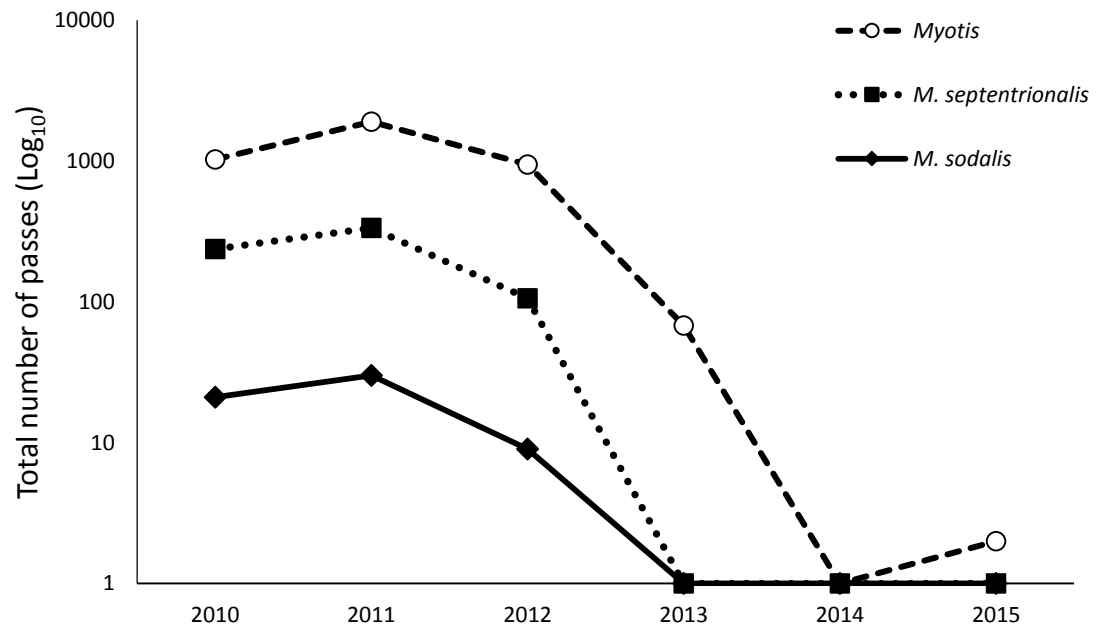


Figure 1.3. Trends in *Myotis* activity (bat passes / year) at Mammoth Cave National Park from 2010 – 2015, as classified using BCID. White-nose syndrome was detected in the park in January of 2013.

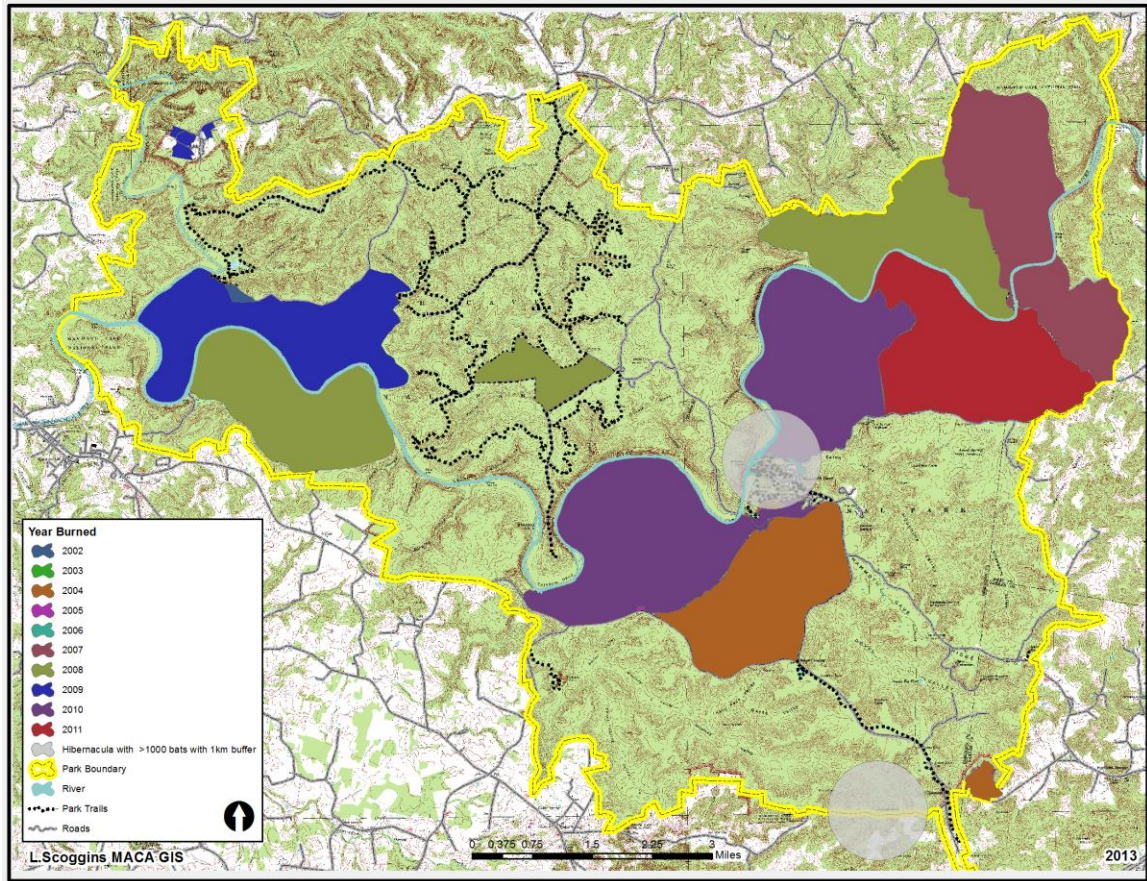


Figure 2.1. Mammoth Cave National Park, Edmondson County, Kentucky history of prescribed fire units and location of bat hibernacula with >1,000 bats. Figure courtesy of the National Park Service.

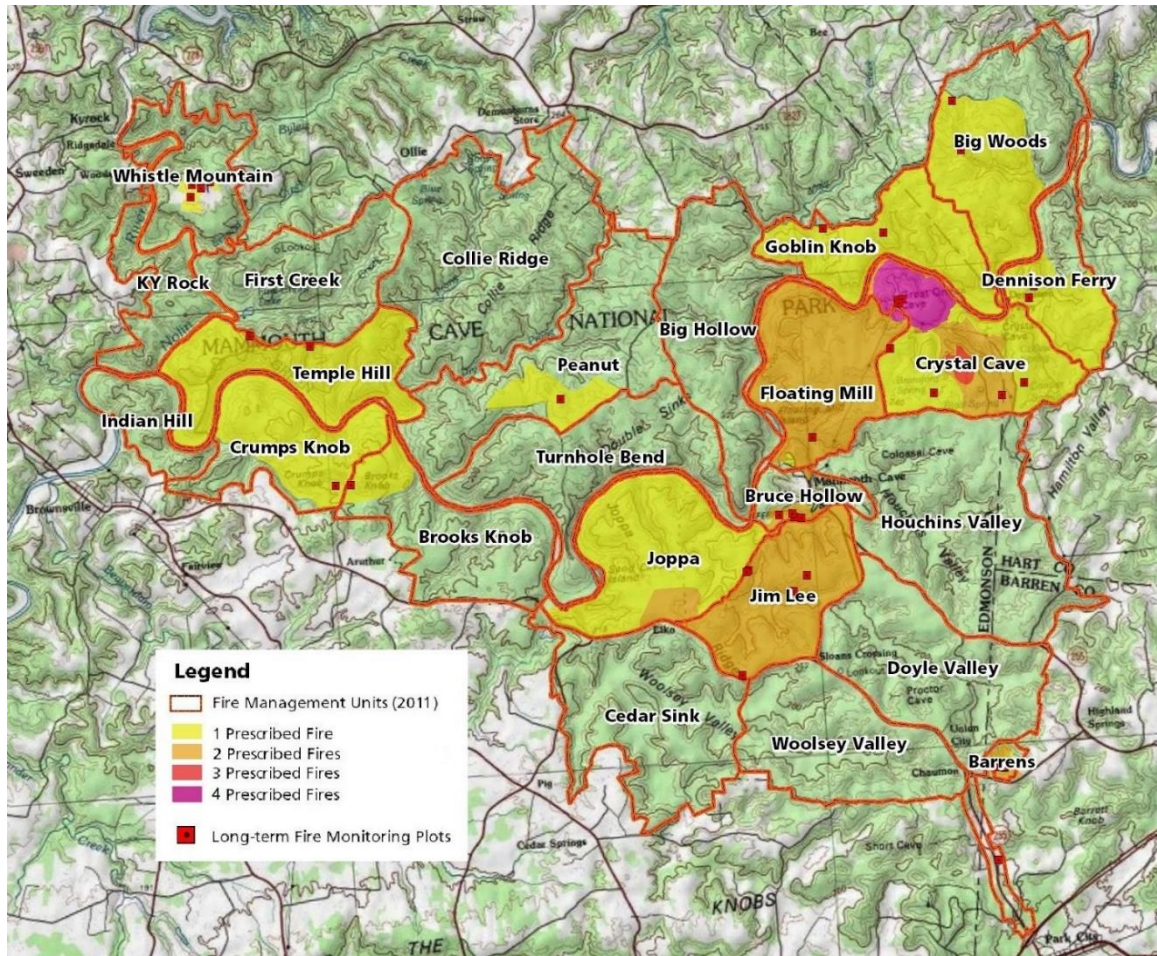
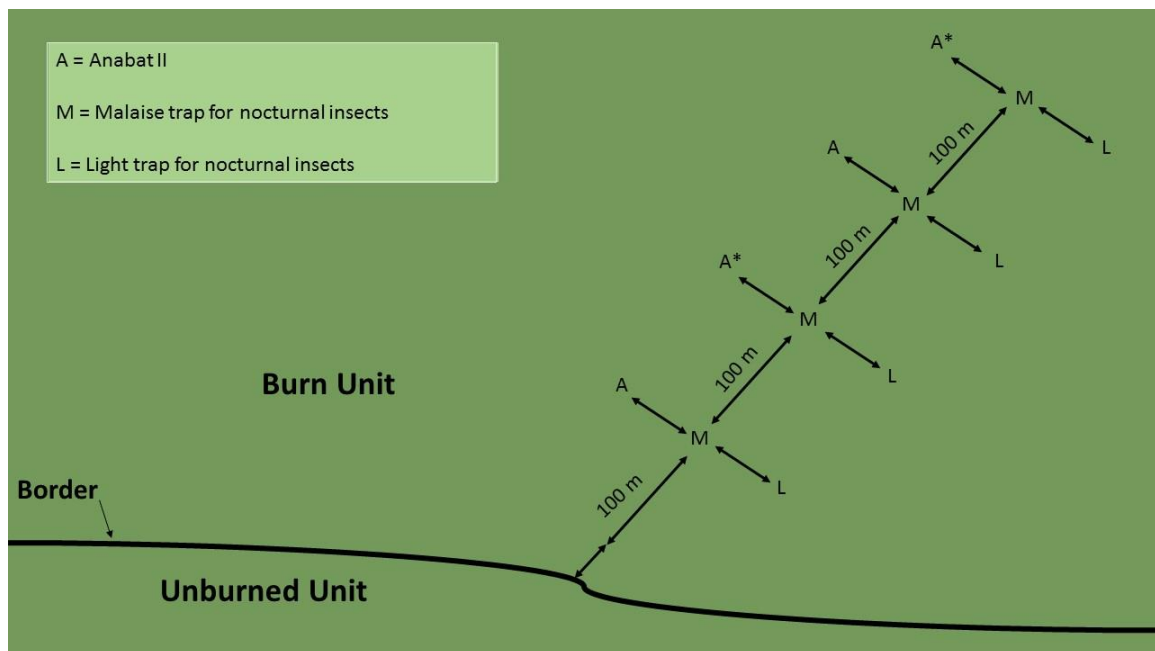


Figure 2.2. Location and number of prescribed burns at Mammoth Cave National Park, Edmondson County, Kentucky. Figure courtesy of the National Park Service.



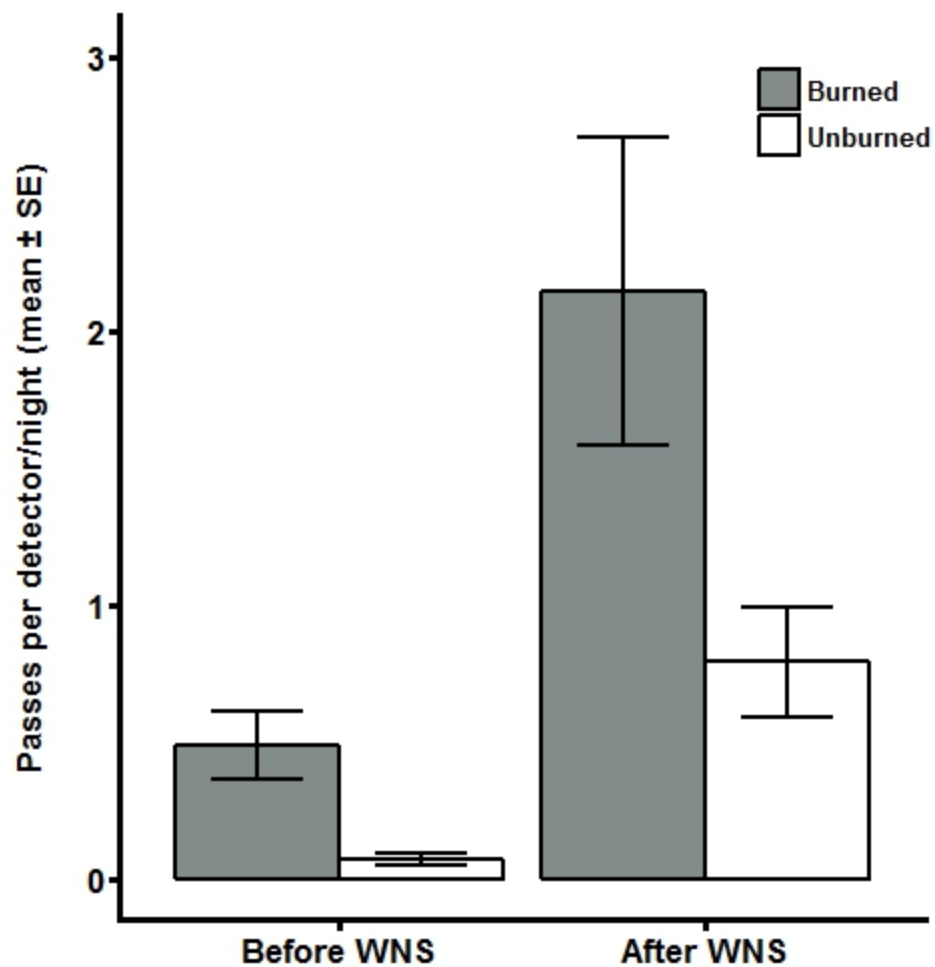


Figure 2.4. Activity of low phonic group bats [passes per/detector night (mean \pm SE)] at Mammoth Cave National Park, Edmondson County, Kentucky, in relation to prescribed fire and white-nose syndrome. Years 2010 – 2012 were before the detection of WNS and 2013 – 2016 were after the detection of WNS.

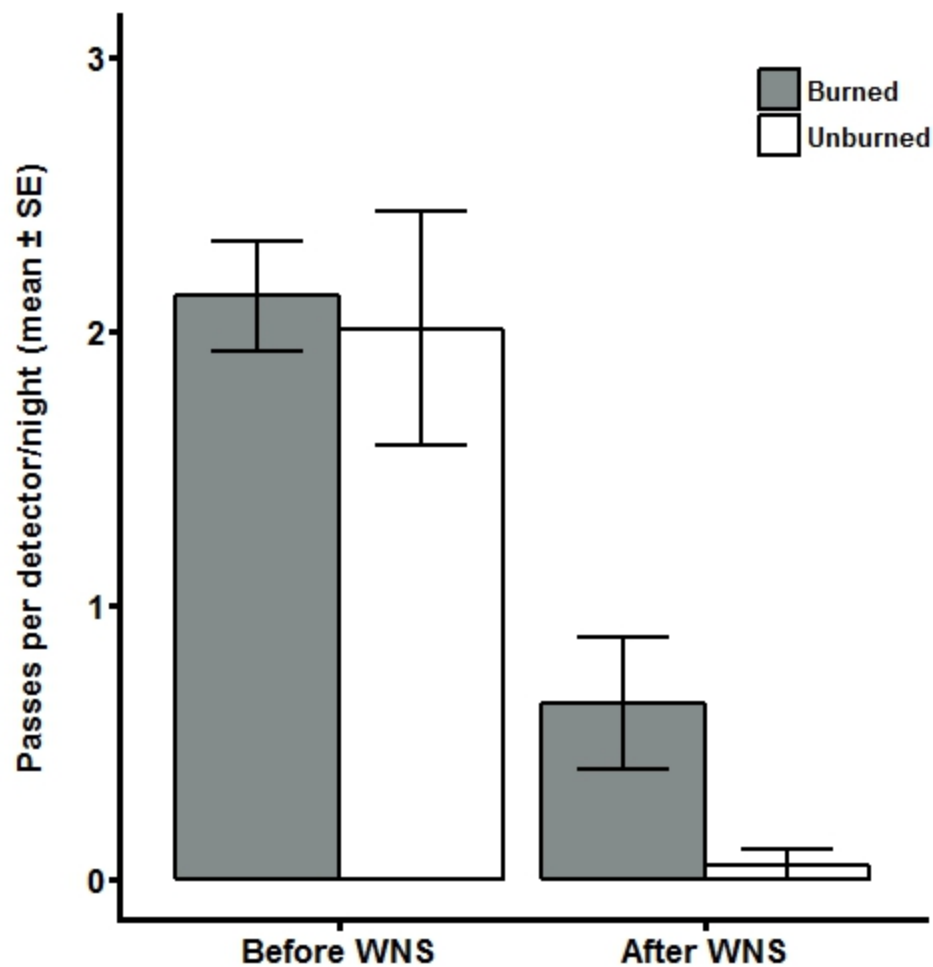


Figure 2.5. Activity of mid phonic group bats [passes per/detector night (mean \pm SE)] at Mammoth Cave National Park, Edmondson County, Kentucky, in relation to prescribed fire and white-nose syndrome. Years 2010 – 2012 were before the detection of WNS and 2013 – 2016 were after the detection of WNS.

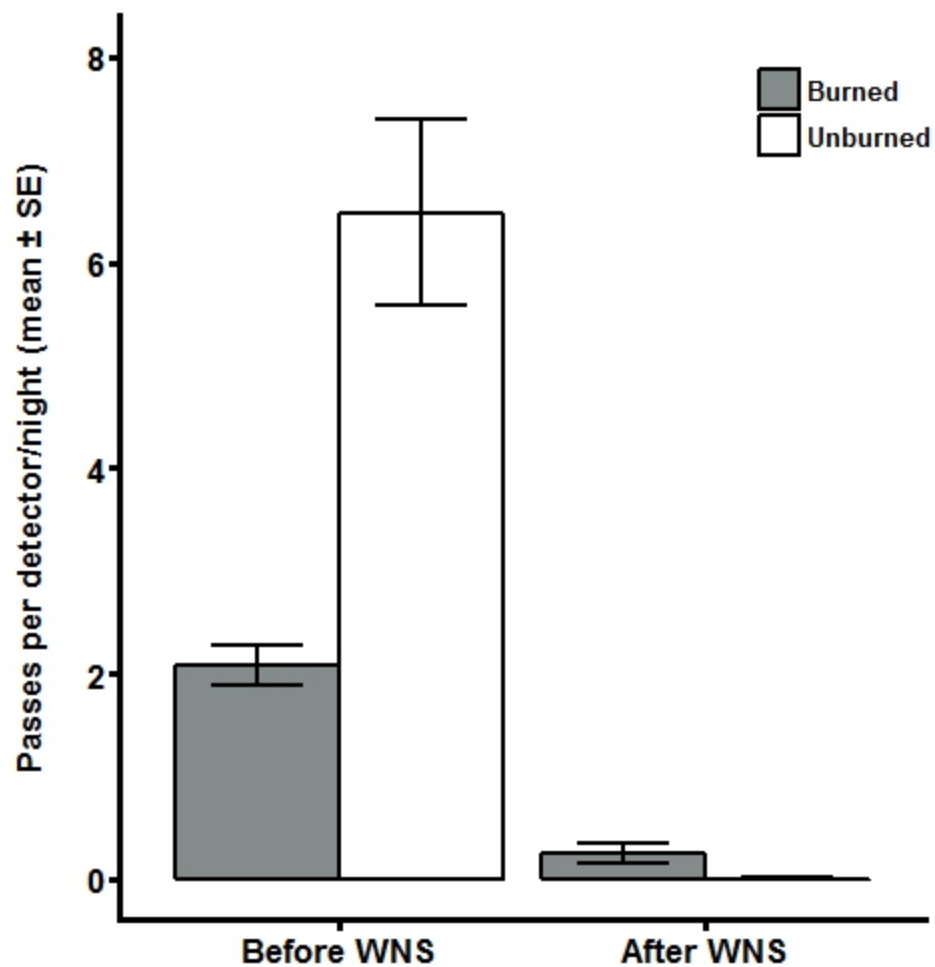


Figure 2.6. Activity of *Myotis* phonic group bats [passes per/detector night (mean \pm SE)] at Mammoth Cave National Park, Edmondson County, Kentucky, in relation to prescribed fire and white-nose syndrome. Years 2010 – 2012 were before the detection of WNS and 2013 – 2016 were after the detection of WNS.

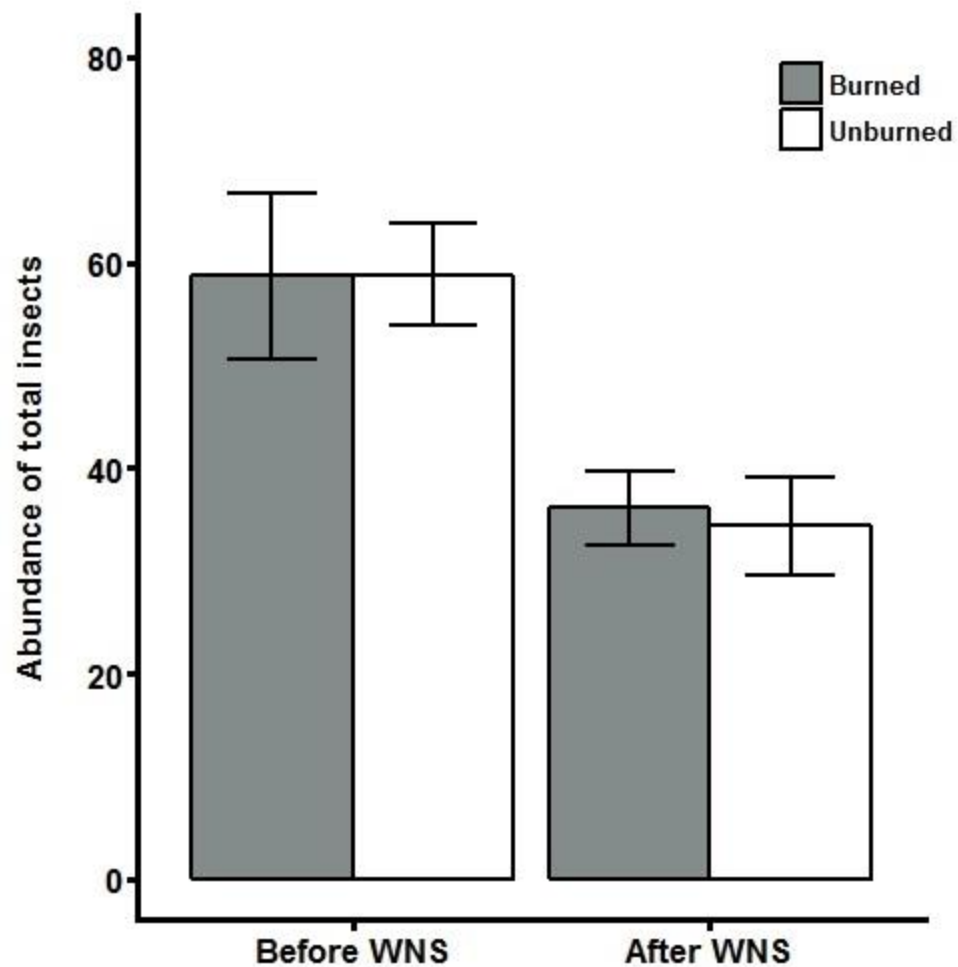


Figure 2.7. Total insect abundance for malaise traps (mean \pm SE) at Mammoth Cave National Park, Edmondson County, Kentucky, in relation to prescribed fire and white-nose syndrome. Years 2010 – 2012 were before the detection of WNS and 2013 – 2016 were after the detection of WNS.

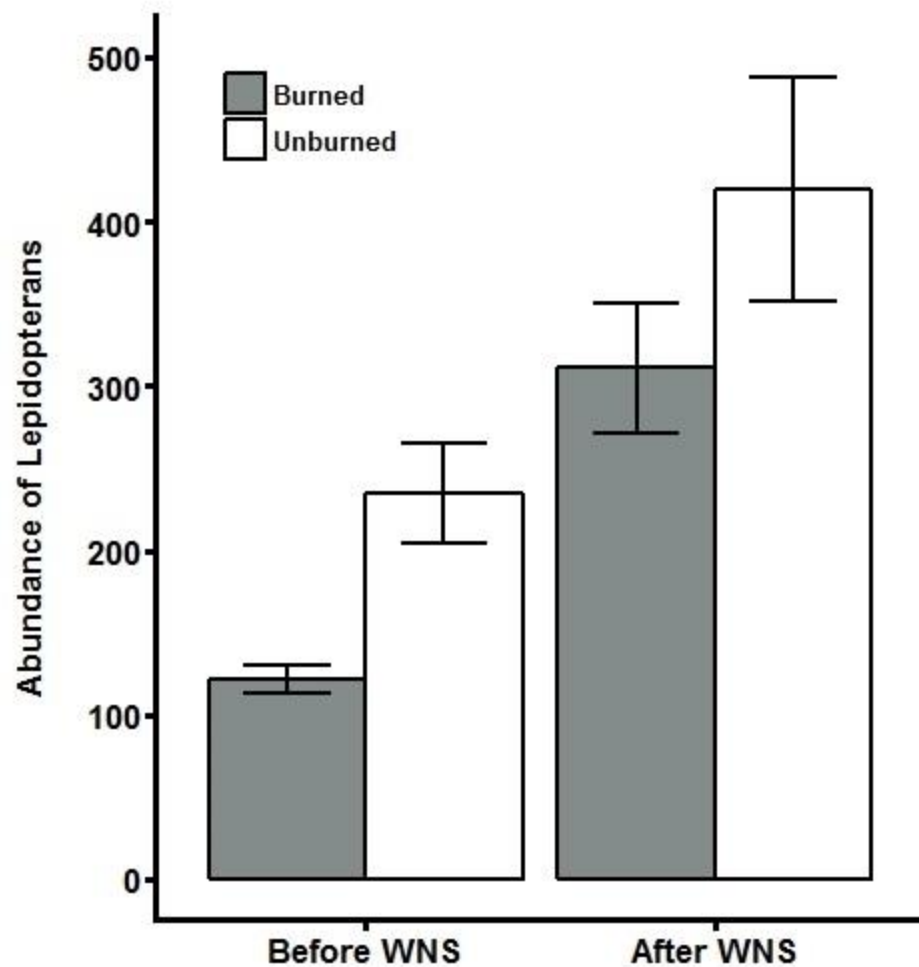


Figure 2.8. Lepidopteran abundance for blacklight traps (mean \pm SE) at Mammoth Cave National Park, Edmondson County, Kentucky, in relation to prescribed fire and white-nose syndrome. Years 2010 – 2012 were before the detection of WNS and 2013 – 2016 were after the detection of WNS.

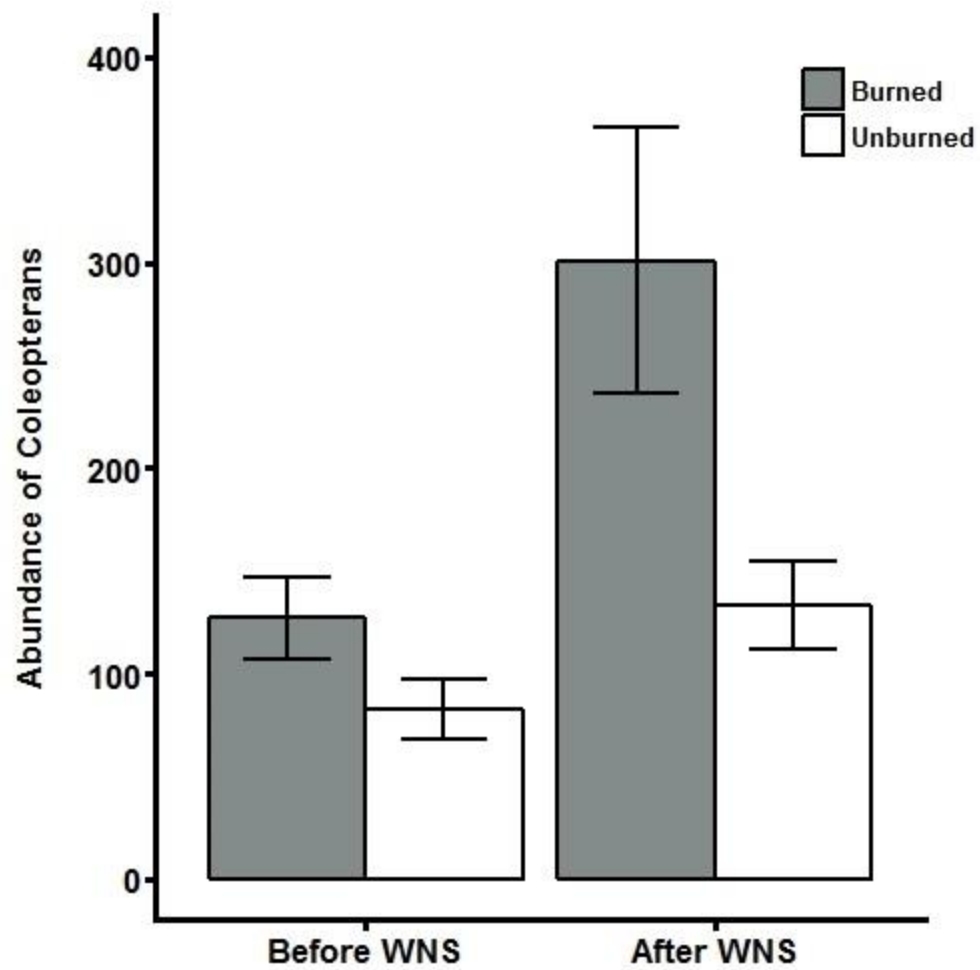


Figure 2.9. Coleopterán abundance for blacklight traps (mean \pm SE) at Mammoth Cave National Park, Edmondson County, Kentucky, in relation to prescribed fire and white-nose syndrome. Years 2010 – 2012 were before the detection of WNS and 2013 – 2016 were after the detection of WNS.

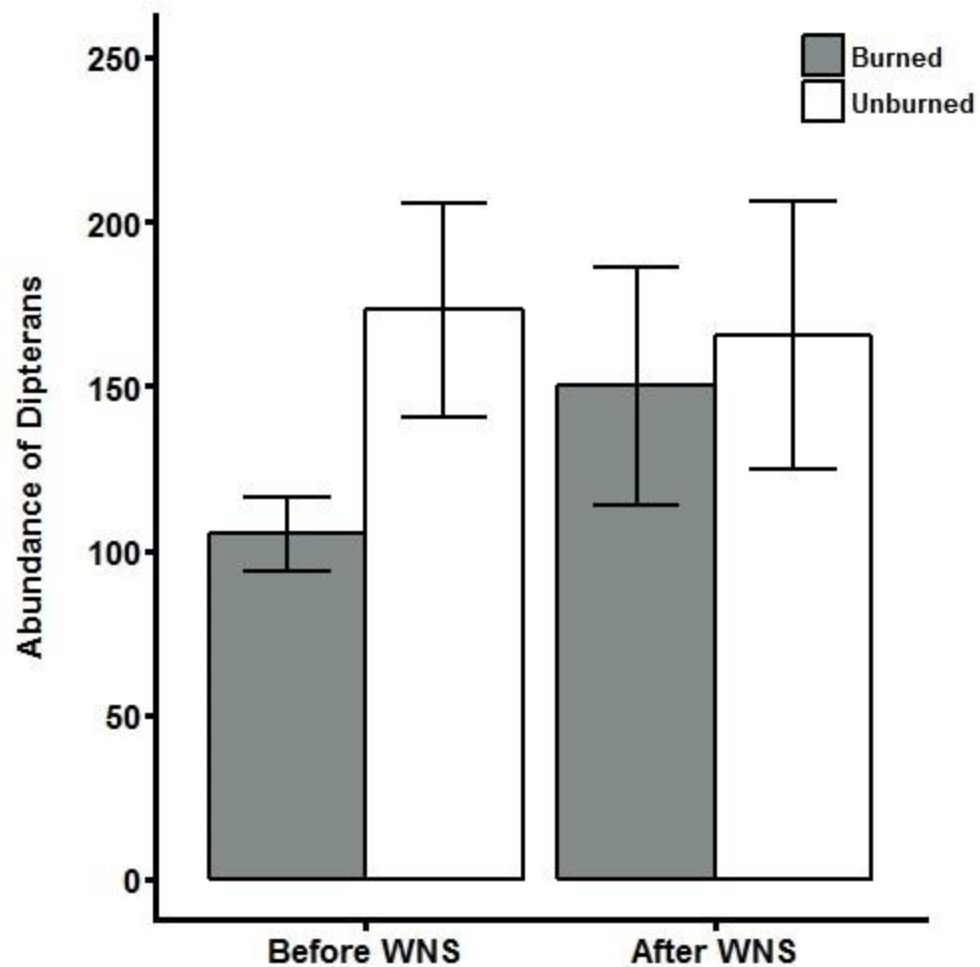


Figure 2.10. Dipteran abundance (mean \pm SE) at Mammoth Cave National Park, Edmondson County, Kentucky, in relation to prescribed fire and white-nose syndrome. Years 2010 – 2012 were before the detection of WNS and 2013 – 2016 were after the detection of WNS.

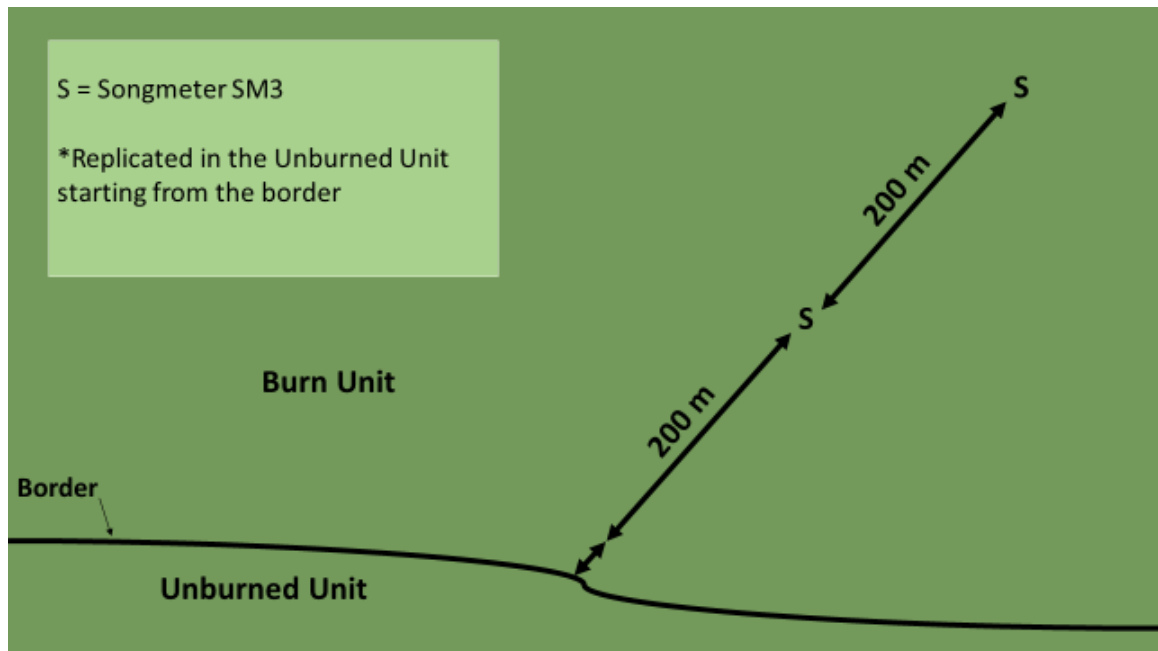


Figure 3.1. Generalized figure of transect used to assess bat activity at Mammoth Cave National Park, Edmondson County, KY. Only burn unit depicted but note this layout was mirrored in an unburned unit as well during each multi-night survey period.

Appendices

Appendix 1. Species-level identifications at 70% confidence interval of echolocation passes recorded at Mammoth Cave National Park, Edmondson County, Kentucky. Surveys at Mammoth Cave National Park spanned the years 2010 – 2016. Species presence was determined using Bat Call ID v. 2.7c. A minimum of 5 pulses were necessary for identification; the minimum discriminate probability for species and phonic group identification was 70%. Species codes are as follows: EPFU (big brown bat), LABO (eastern red bat), LACI (hoary bat), LANO (silver-haired bat), MYGR (gray bat), MYLE (eastern small-footed bat), MYLU (little brown bat), MYSE (northern long-eared bat), MYSO (Indiana bat), NYHU (evening bat), and PESU (tri-colored bat).

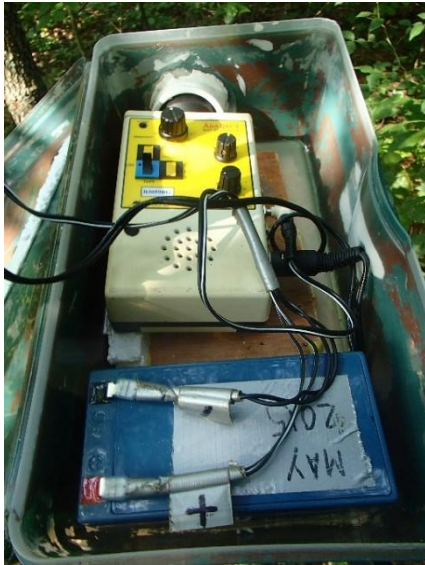
WNS	Year	Habitat	Species											Phonic Group		
			EPFU	LABO	LACI	LANO	MYGR	MYLE	MYLU	MYSE	MYSO	NYHU	PESU	Low	Mid	<i>Myotis</i>
Before WNS	2010	Burned	17	14	1	47	97	17	15	128	62	23	209	65	246	319
		Unburned	3	7	4	1	120	5	7	368	88	12	111	8	130	588
	2011	Burned	140	41	3	31	44	7	21	244	63	162	187	174	390	379
		Unburned	5	23	0	7	48	5	37	598	107	35	81	12	139	795
	2012	Burned	21	17	0	6	137	28	22	99	41	102	76	27	195	327
		Unburned	3	3	0	0	127	3	12	152	23	76	54	3	133	317
After WNS	2013	Burned	3	3	0	0	16	0	4	1	10	10	55	3	68	31
		Unburned	0	0	0	0	0	0	0	0	0	0	7	0	7	0
	2014	Burned	1	0	96	0	0	0	0	0	0	0	0	97	0	0
		Unburned	0	0	47	0	0	0	0	0	0	0	0	47	0	0
	2015	Burned	18	0	209	7	1	0	0	0	1	1	4	234	5	2
		Unburned	0	0	38	0	0	0	0	0	0	0	0	38	0	0
	2016	Burned	3	0	162	2	0	0	0	0	0	0	0	167	0	0
		Unburned	1	0	6	0	0	0	0	0	0	0	0	7	0	0

Appendix 3. Capture success of insects from blacklight and malaise traps at Mammoth Cave National Park, Edmondson County, Kentucky. Surveys spanned 2010 - 2012 and 2015 – 2016.

WNS	Year	Habitat	Orders				Total Insects
			Lepidoptera	Coleoptera	Diptera	Other orders	
Before WNS	2010	Burned	4977	772	1686	2006	9441
		Unburned	8704	645	2479	1250	13087
	2011	Burned	8881	14201	10576	9833	43491
		Unburned	11707	5510	12456	8474	38147
	2012	Burned	11518	10793	14729	33080	70120
		Unburned	7300	3459	9606	3263	23628
After WNS	2015	Burned	10255	5294	6282	4453	26284
		Unburned	9784	2177	4464	1405	17830
	2016	Burned	9239	13394	4661	23644	50938
		Unburned	4637	2373	2147	5031	14188

Appendix 4. Zero-crossing acoustic detector, Anabat II system, (Titley Electronics, Colombia, MO) deployment method at Mammoth Cave National Park, Edmondson County, Kentucky, during 2010-2016. A) Anabat II detector unit housed in plastic protective case with external power source. B) Anabat II detector unit deployed 1.5 m above ground on tripod.

A)



B)



Appendix 5. Full-spectrum acoustic detector, Songmeter SM3 (“Bat+” option, Wildlife Acoustics Inc., Maynard, MA) deployment method at Mammoth Cave National Park, Edmondson County, Kentucky, during 2015-2016. A) Songmeter SM3 unit housed in plastic protective case. B) Songmeter SM3 microphone housed in plastic protective casing and deployed 3.0 m above ground with unit at base of the tree.

A)



B)



Appendix 6. Blacklight trap deployment method for insect sampling at Mammoth Cave National Park, Edmondson County, Kentucky, during 2010-2012 and 2015-2016. Blacklight suspended 2.5 m above ground and operated from sunset to sunrise. External power source deployed in a plastic protective bag at the base of the tree.



Appendix 7. Malaise trap deployment method for insect sampling at Mammoth Cave National Park, Edmondson County, Kentucky, during 2010-2012 and 2015-2016.

